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(54) **USING DEPTH-CAMERA IMAGES TO SPEED REGISTRATION OF THREE-DIMENSIONAL SCANS**

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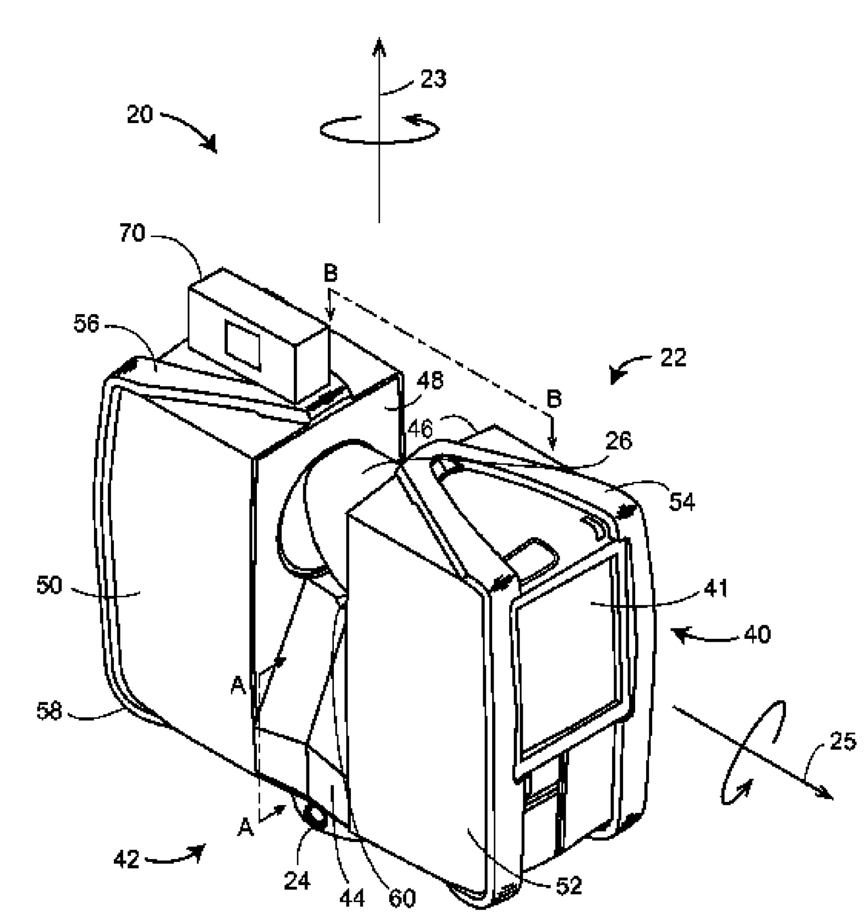
(57) **ABSTRACT**

A method for measuring and registering 3D coordinates has a 3D scanner measure a first collection of 3D coordinates of points from a first registration position and a second collection of 3D coordinates of points from a second registration position. In between these positions, the 3D measuring device collects depth-camera images. A processor determines first and second translation values and a first rotation value based on the depth-camera images. The processor identifies a correspondence among registration targets in the first and second collection of 3D coordinates based at least in part on the first and second translation values and the first rotation value. The processor uses this correspondence and
(Continued)



the first and second collection of 3D coordinates to determine 3D coordinates of a registered 3D collection of points.

16 Claims, 16 Drawing Sheets

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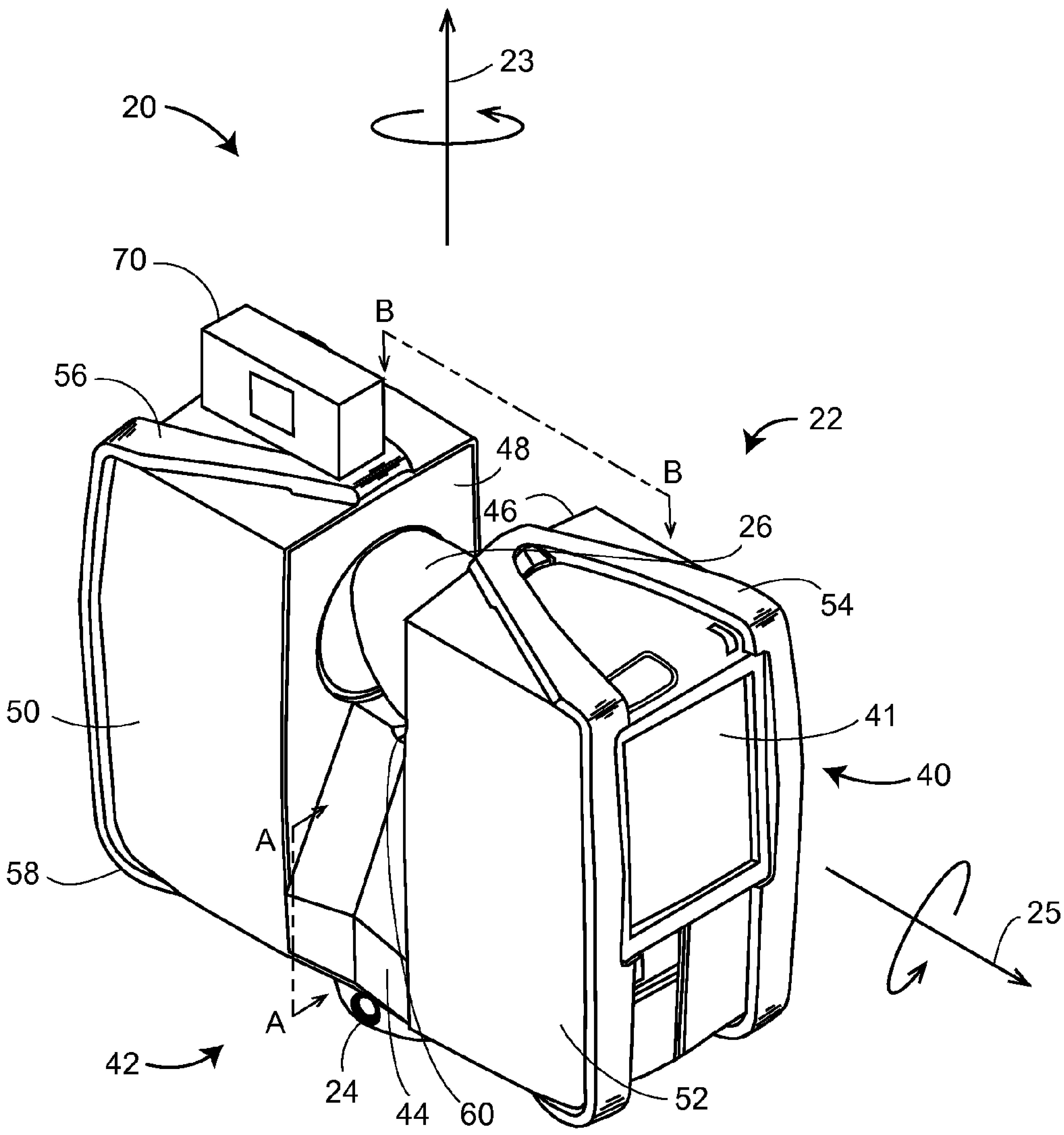


FIG. 1

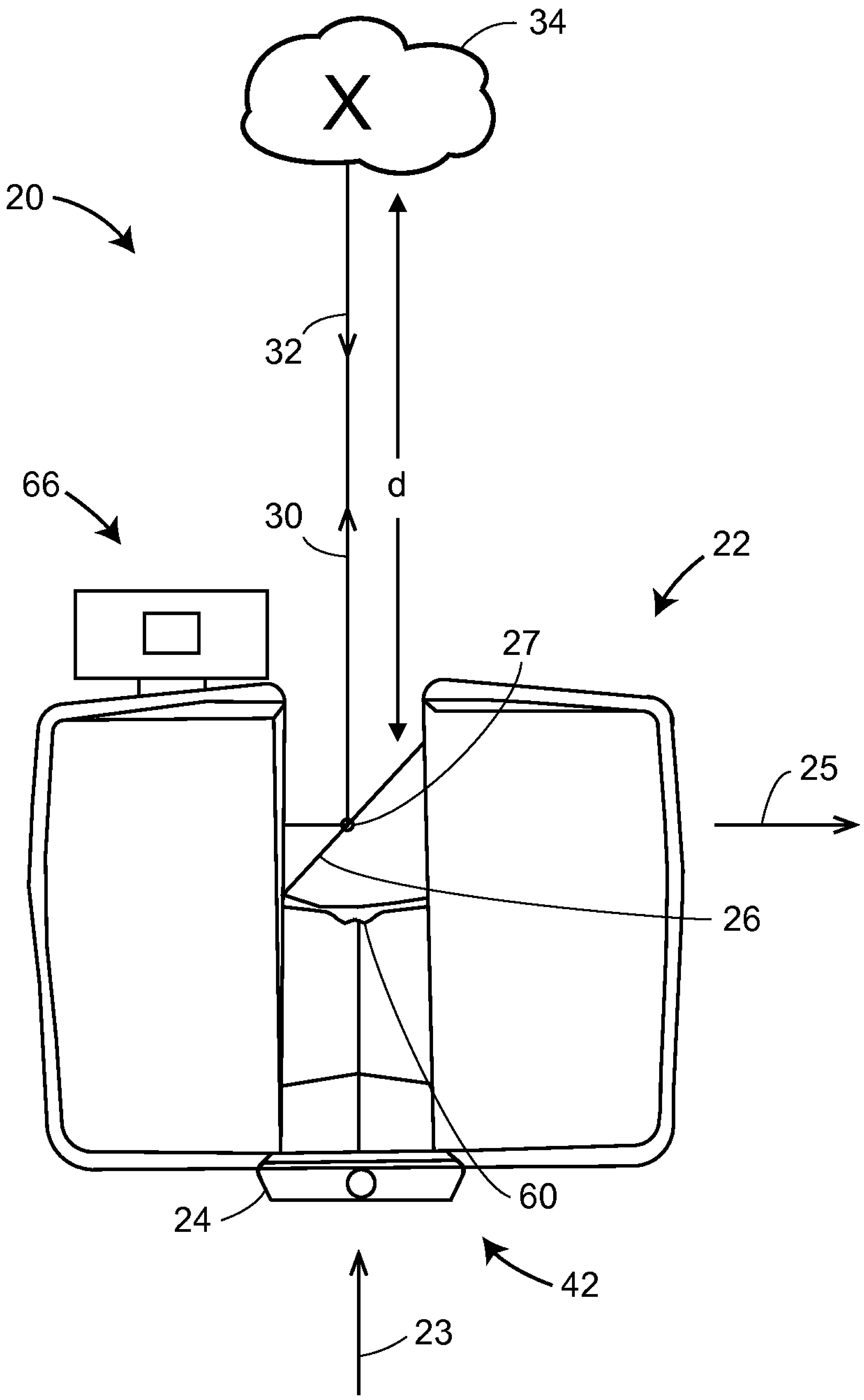


FIG. 2

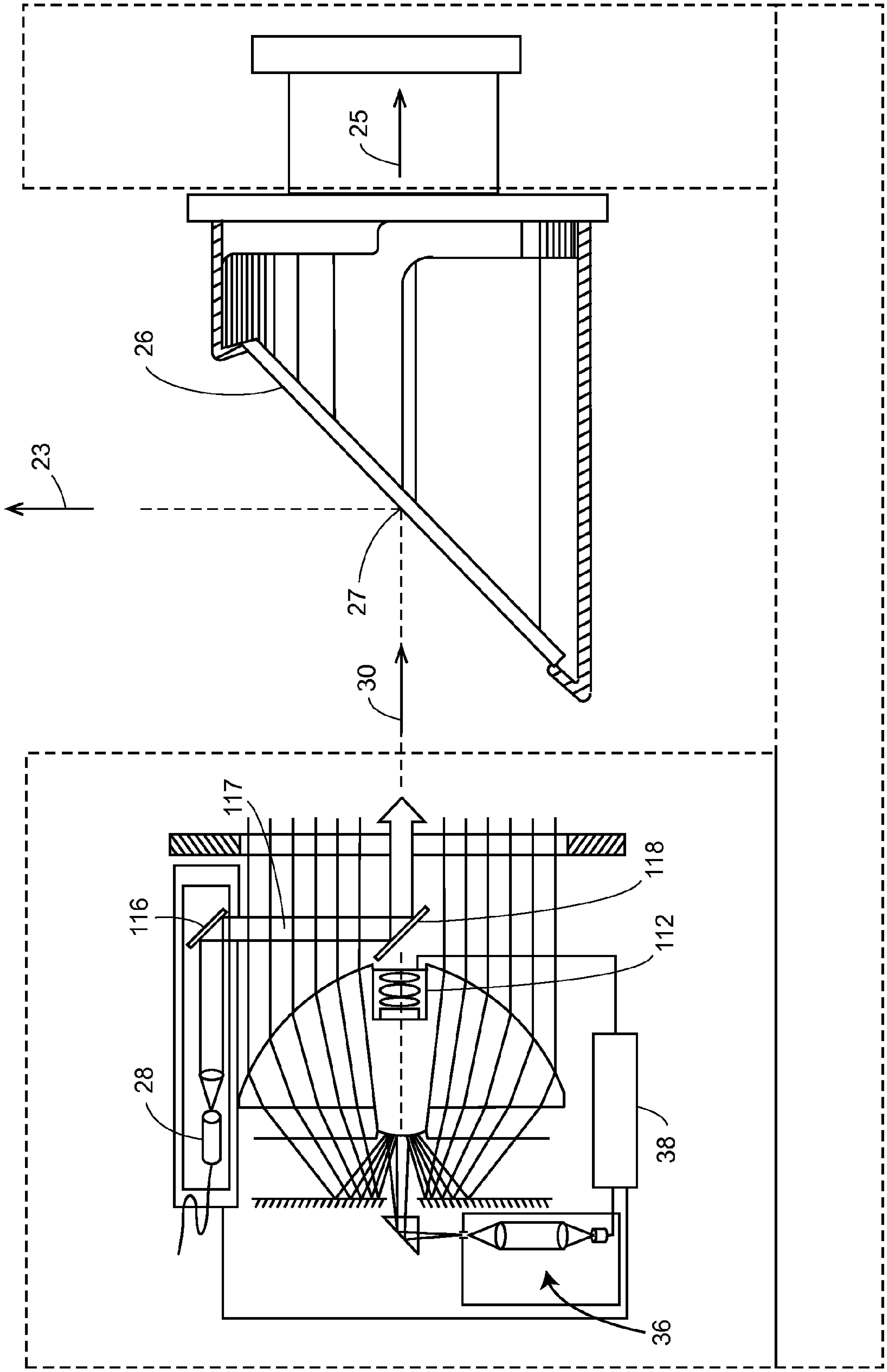
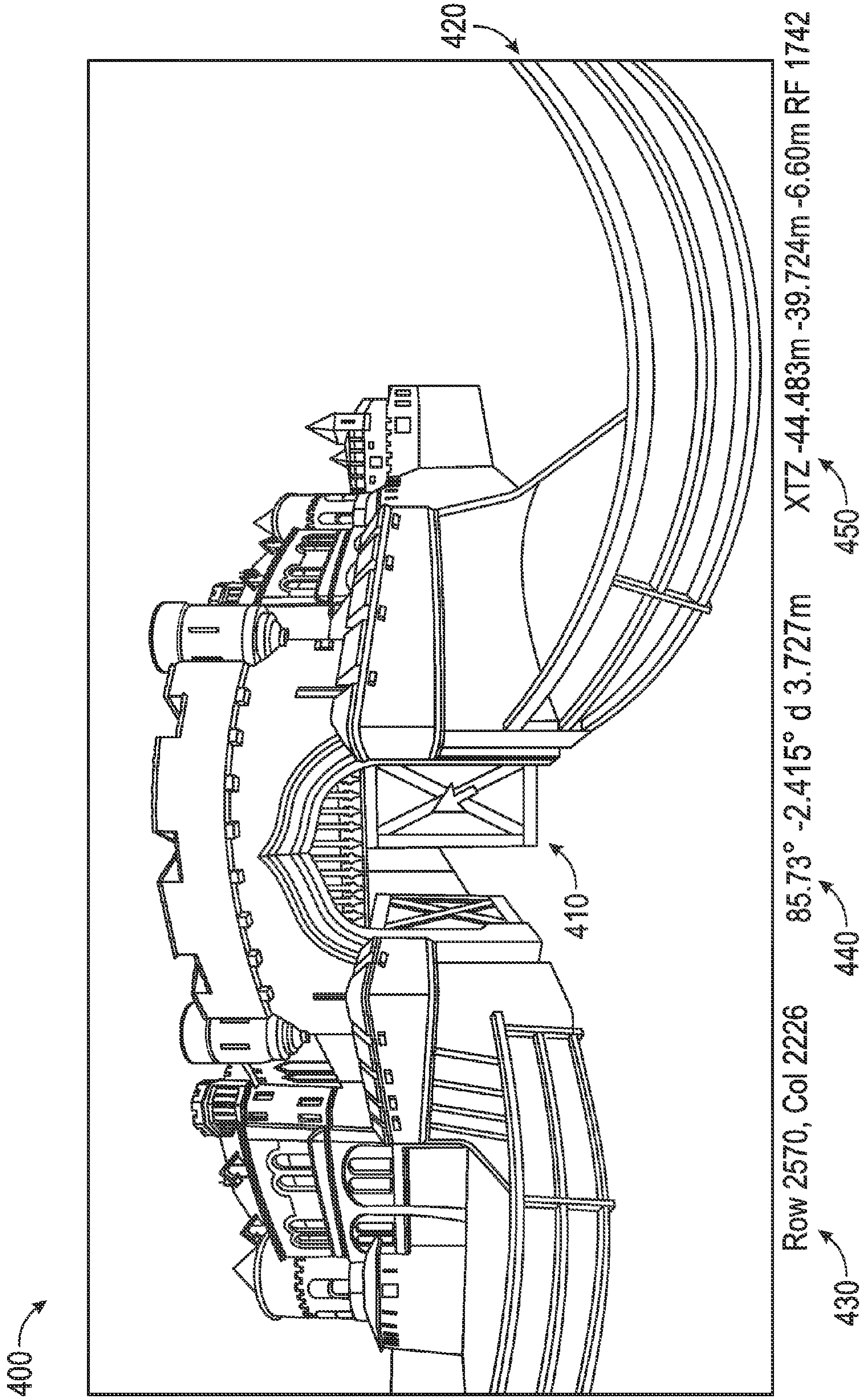


FIG. 3



400
410
420
Row 2570, Col 2226
430
85.73° -2.415° d 3.727m
440
XTZ -44.483m -39.724m -6.60m RF 1742
450

FIG. 4

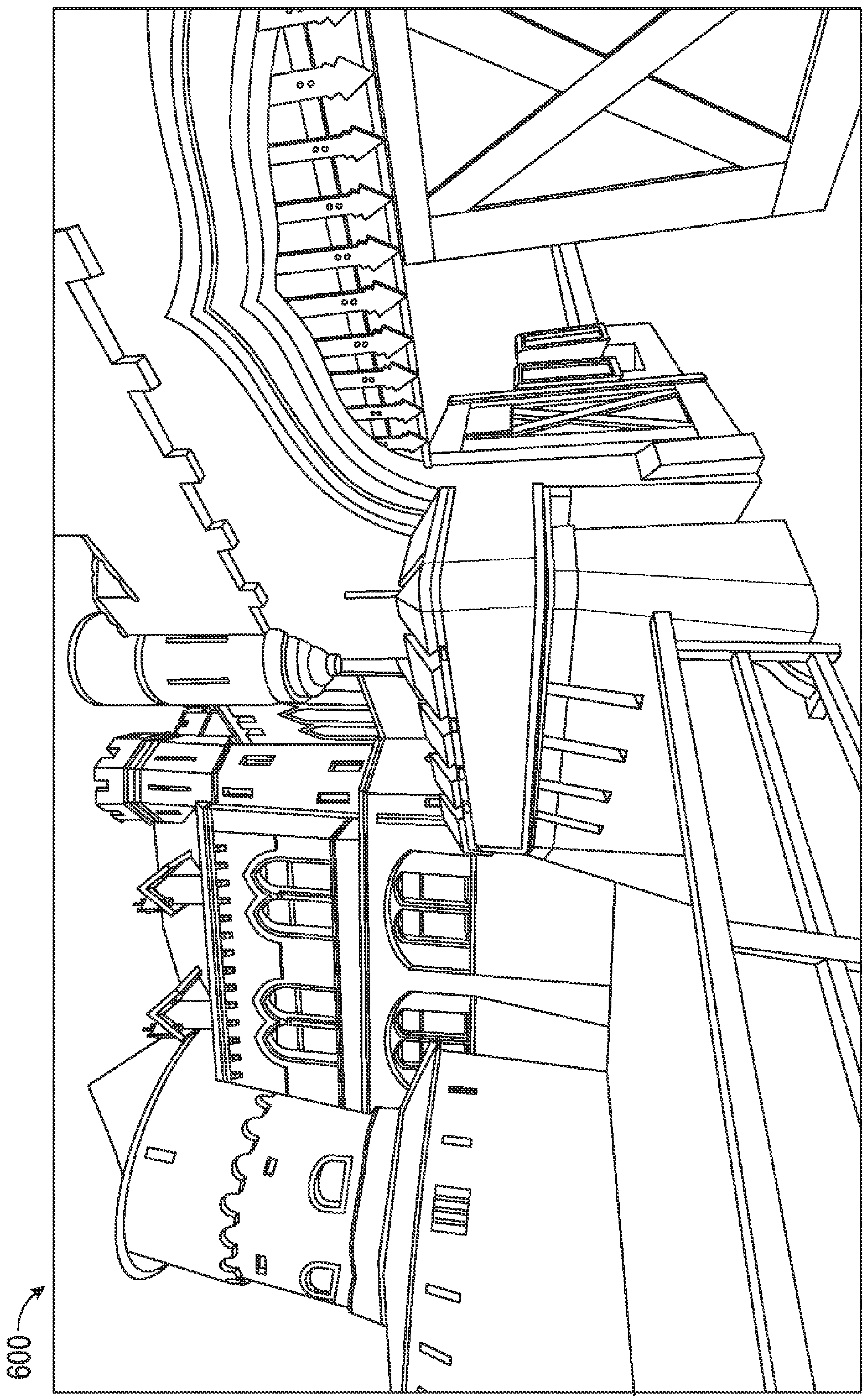


FIG. 5

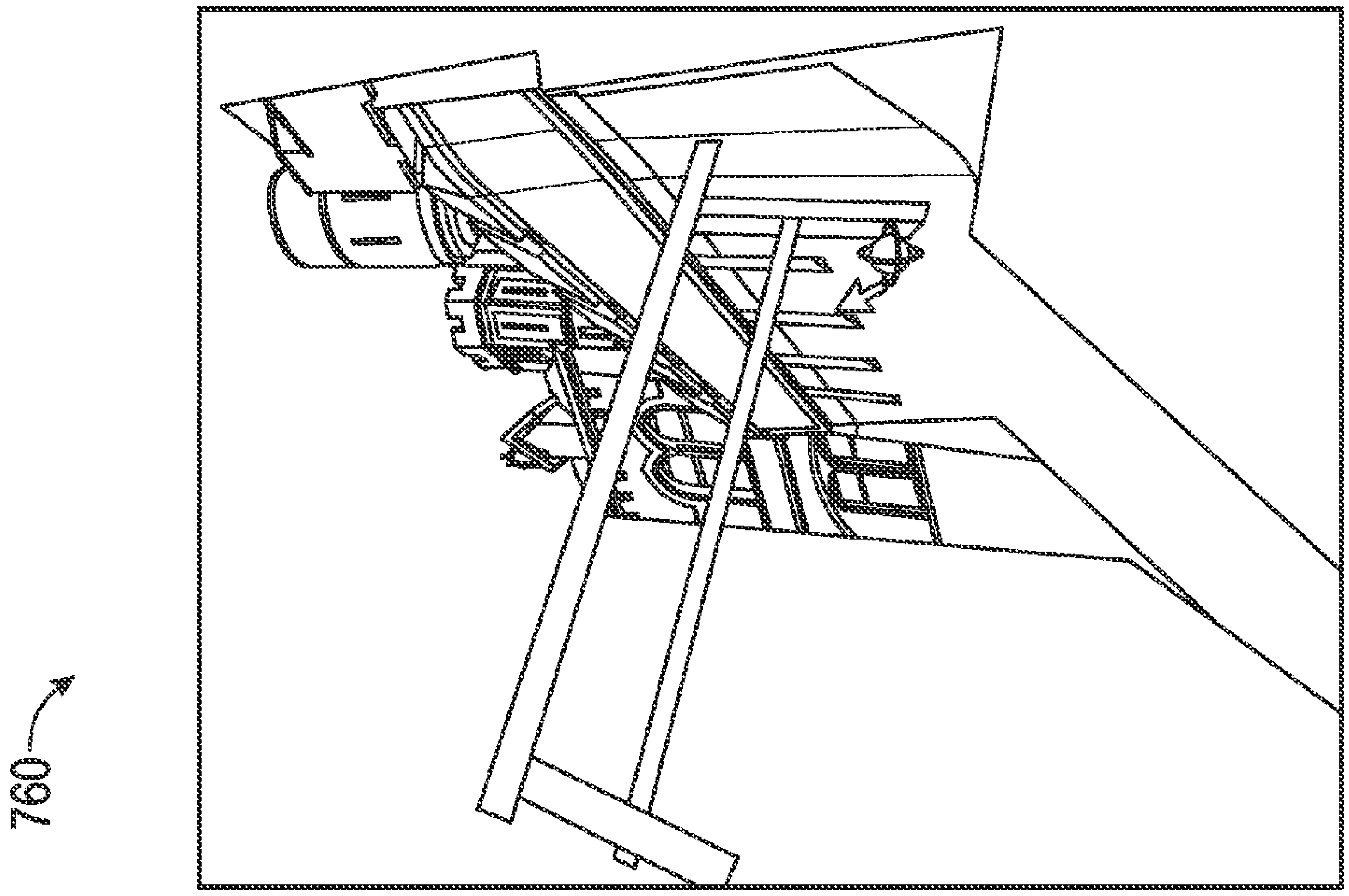


FIG. 6C

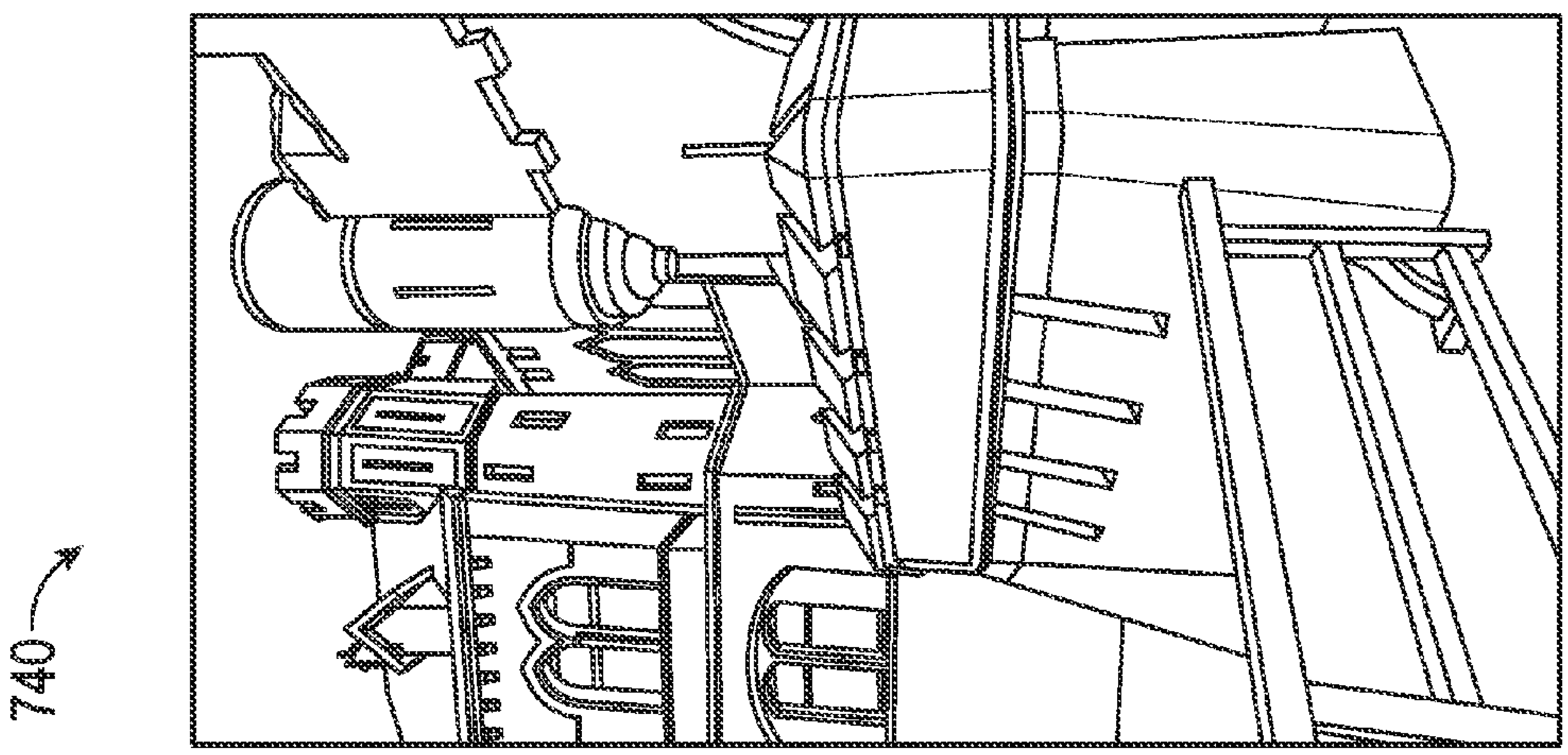


FIG. 6B

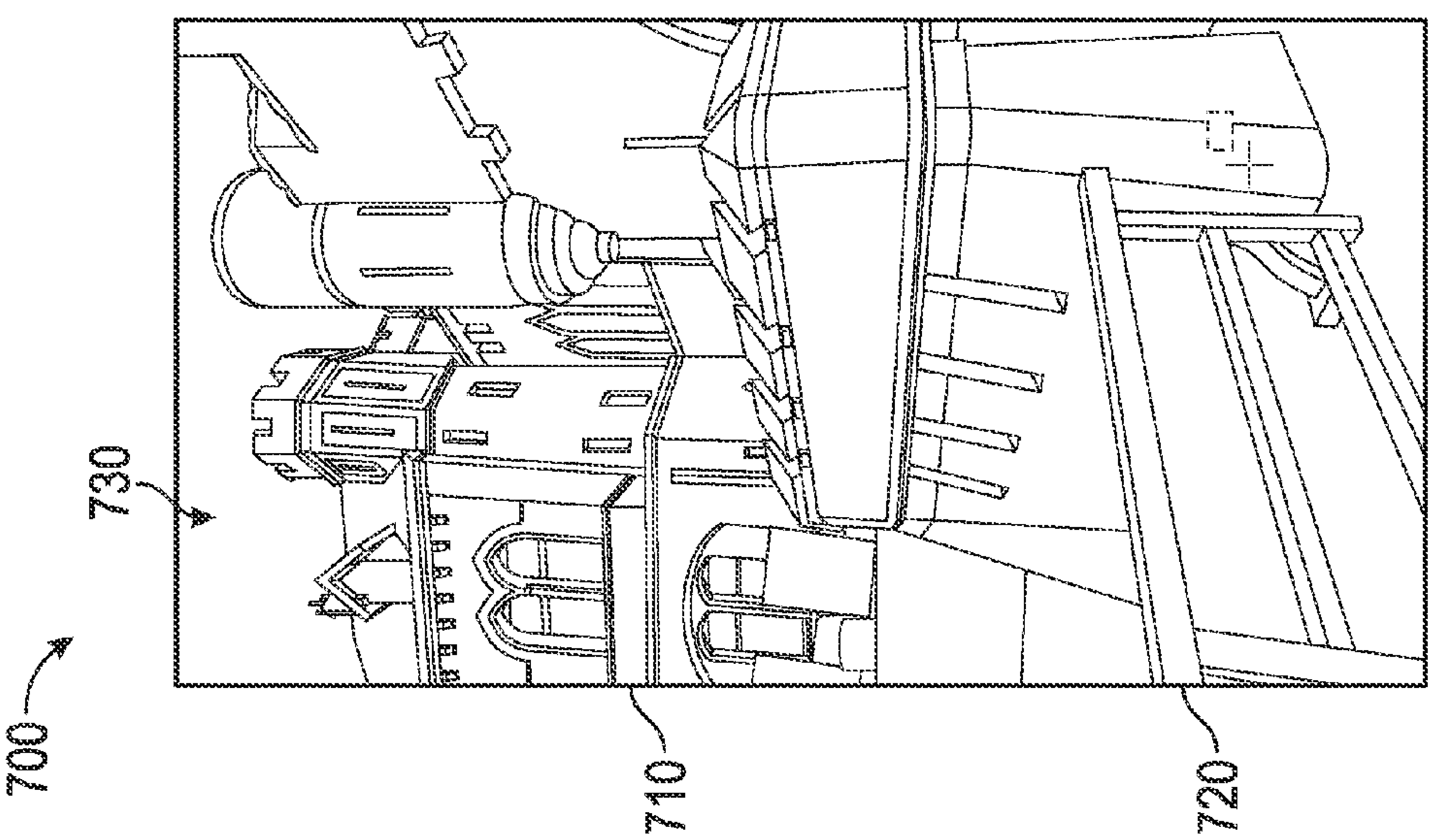


FIG. 6A

800

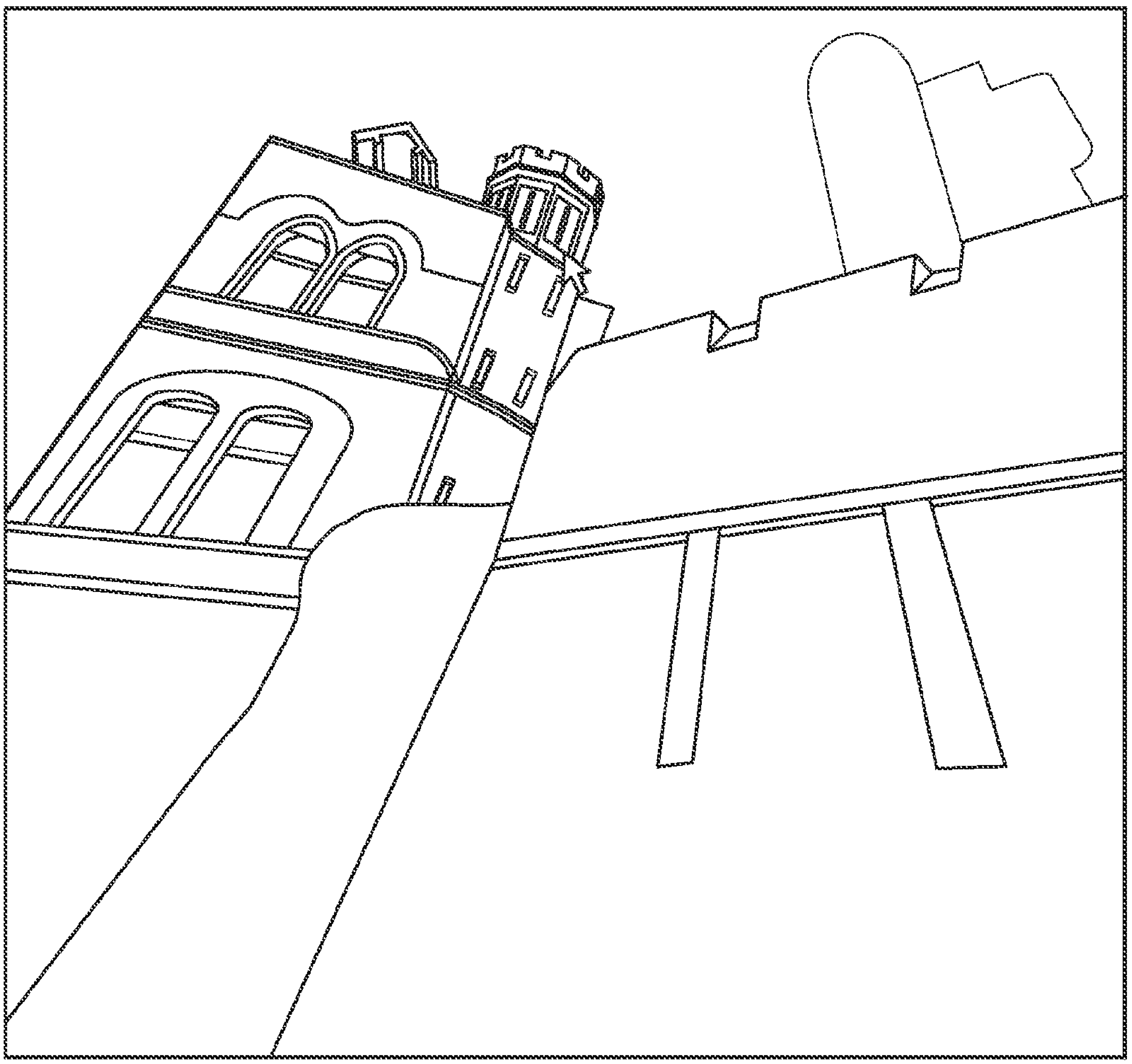


FIG. 7

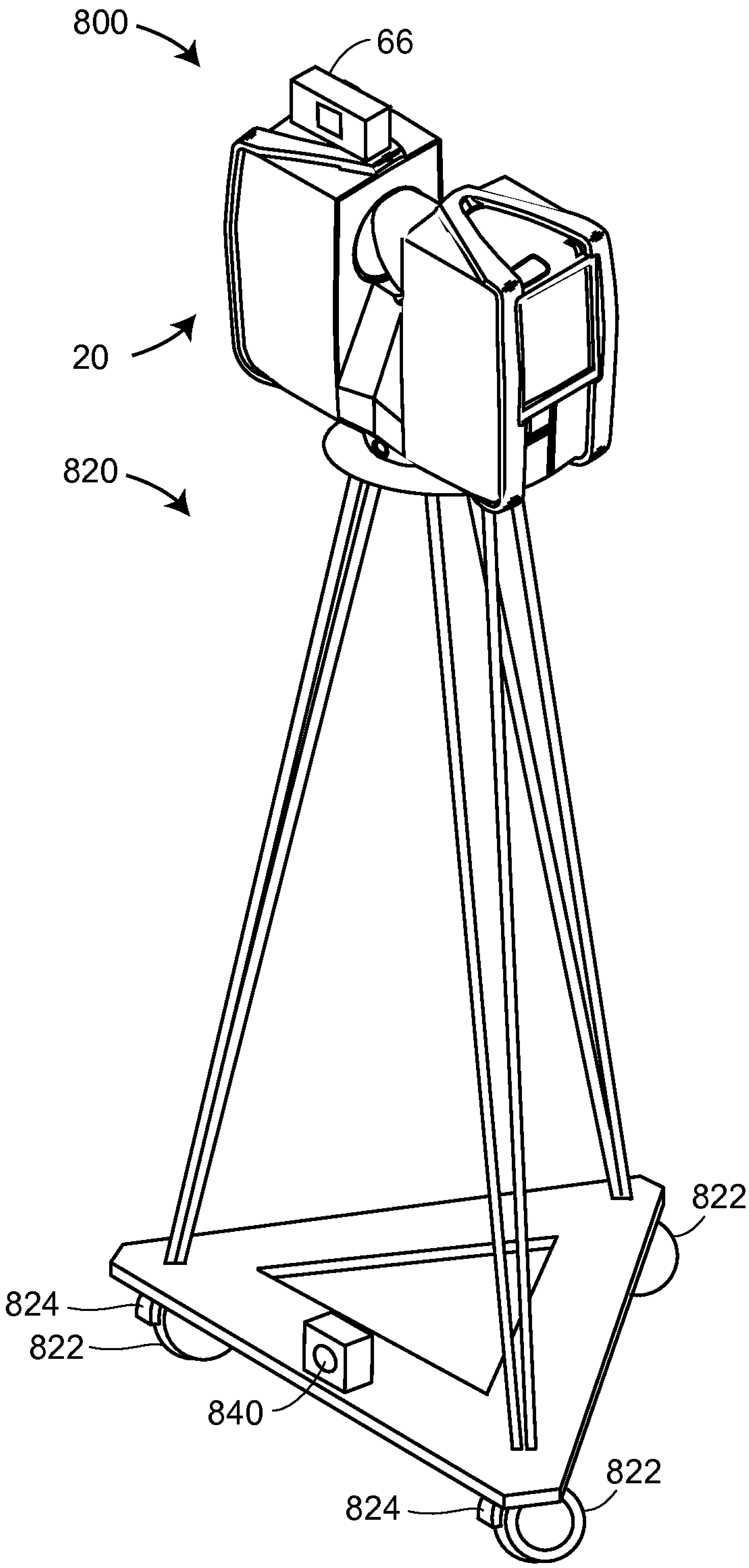


FIG. 8A

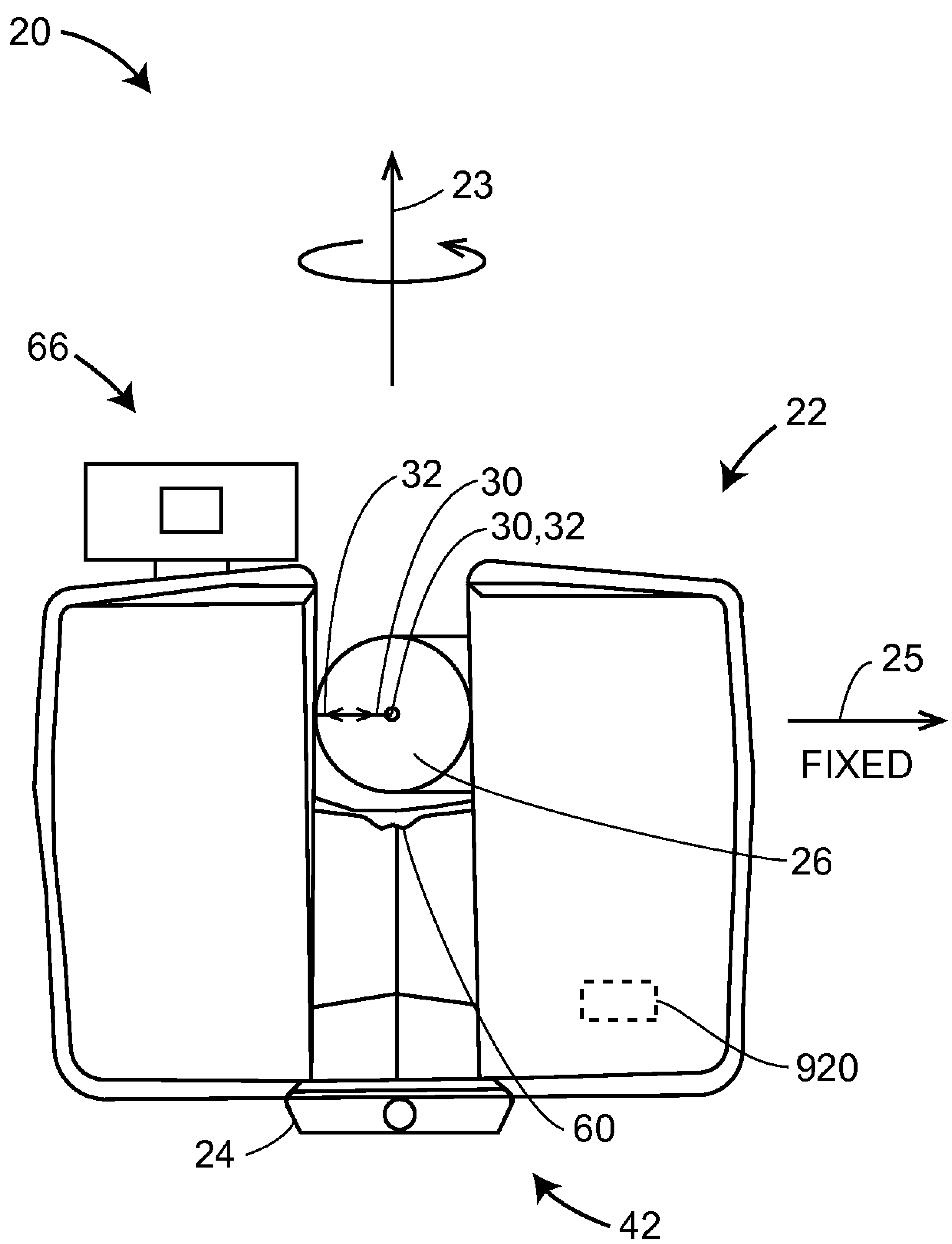


FIG. 8B

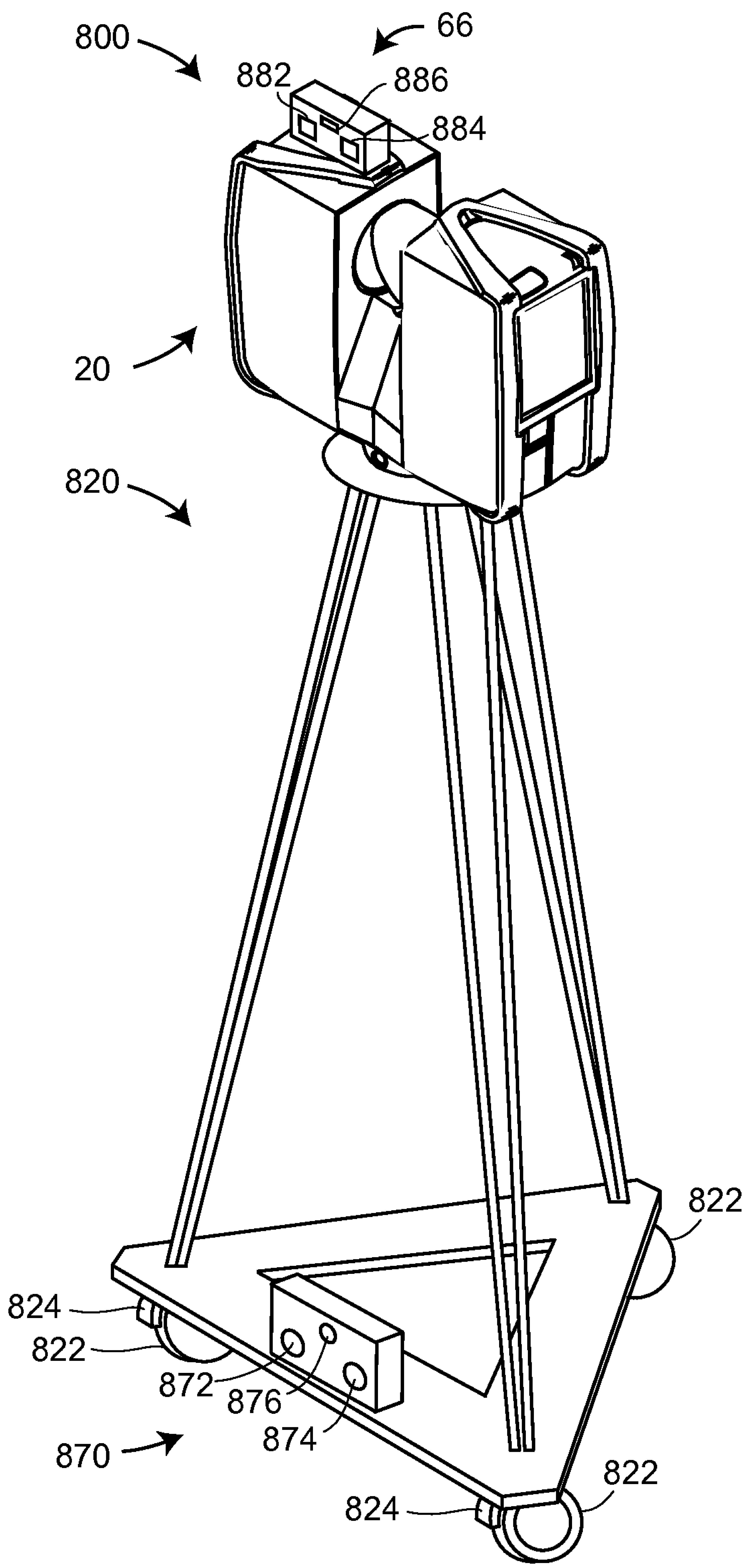


FIG. 8C

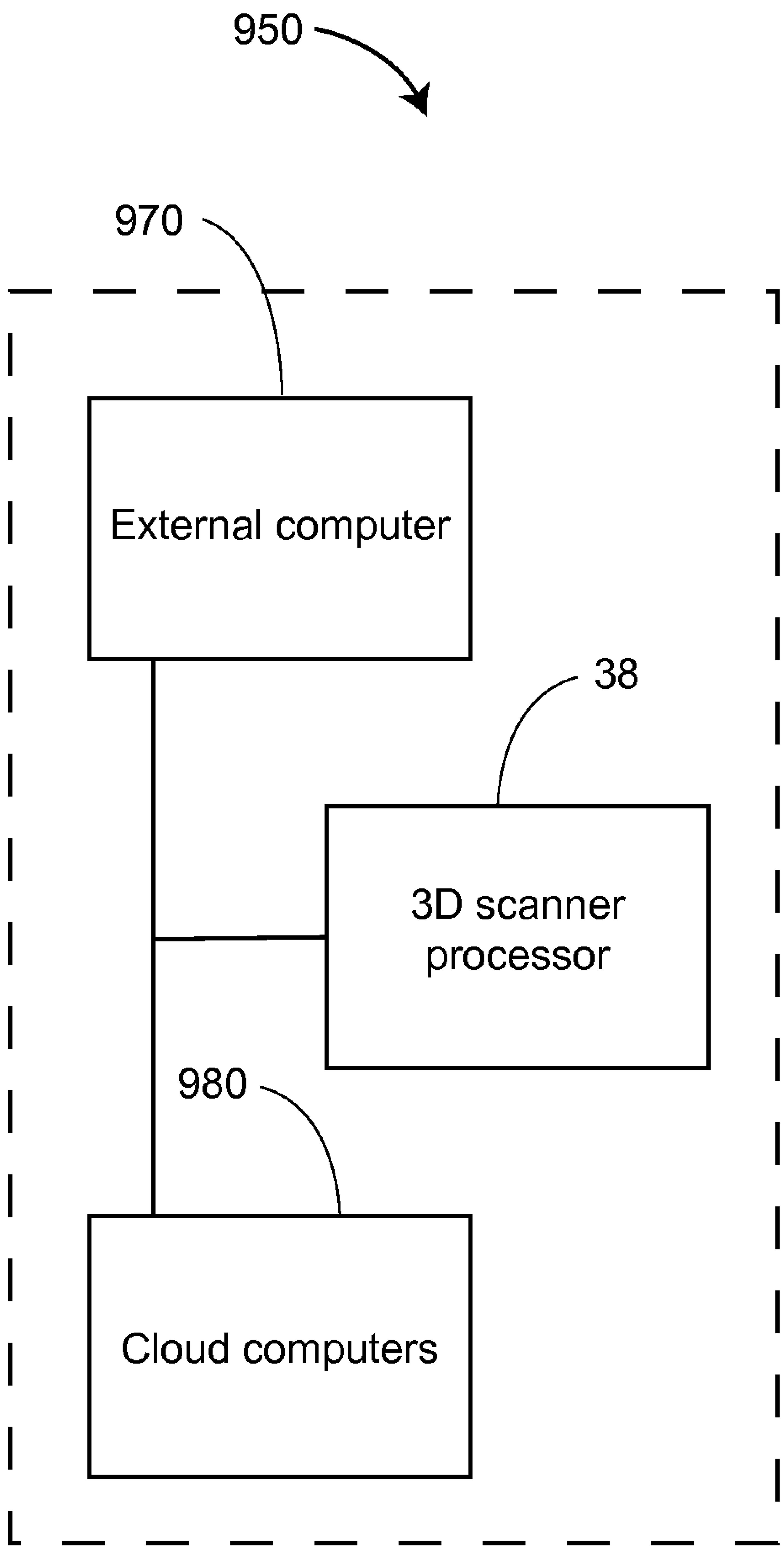
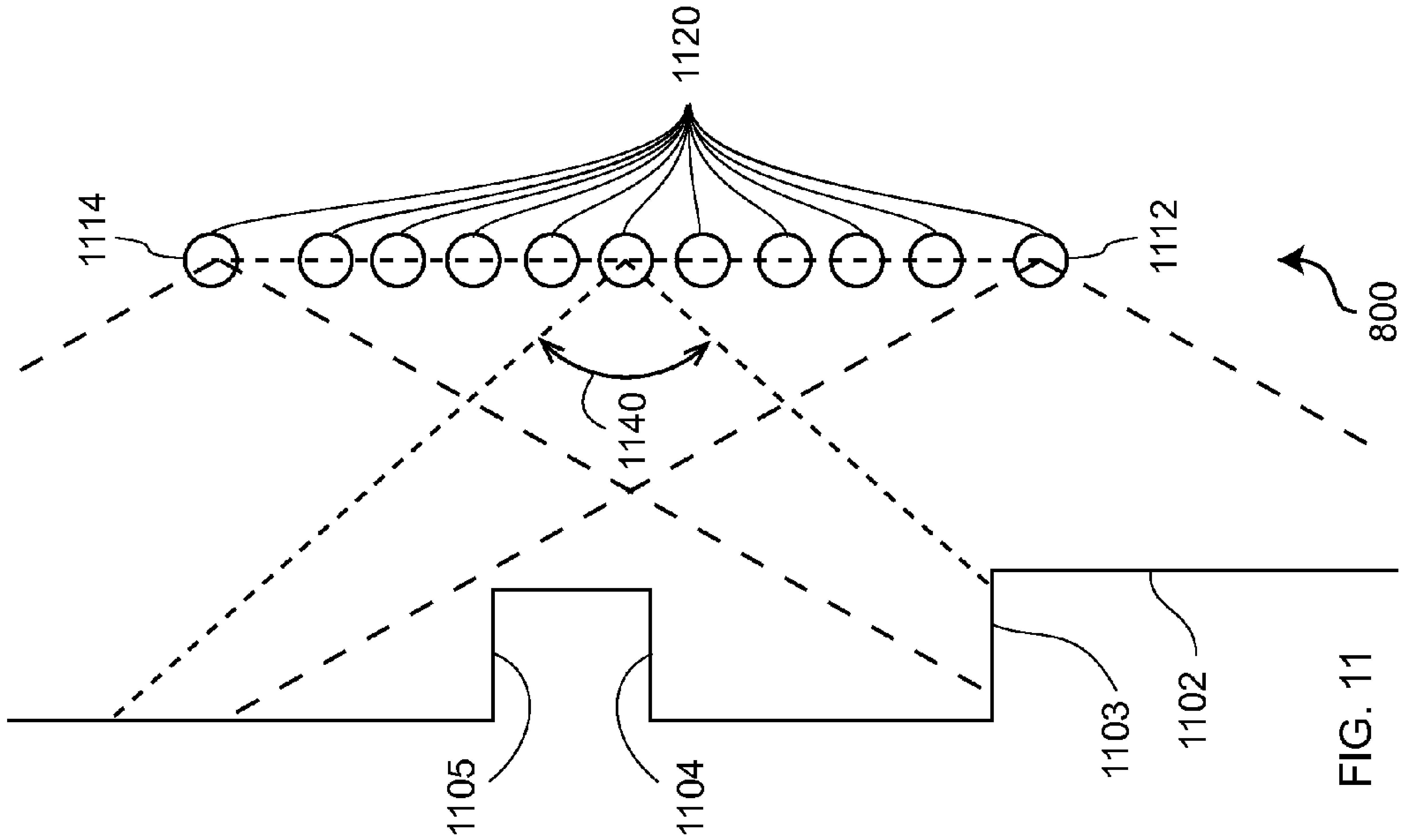

950
970
External computer
38
3D scanner
processor
980
Cloud computers

FIG. 9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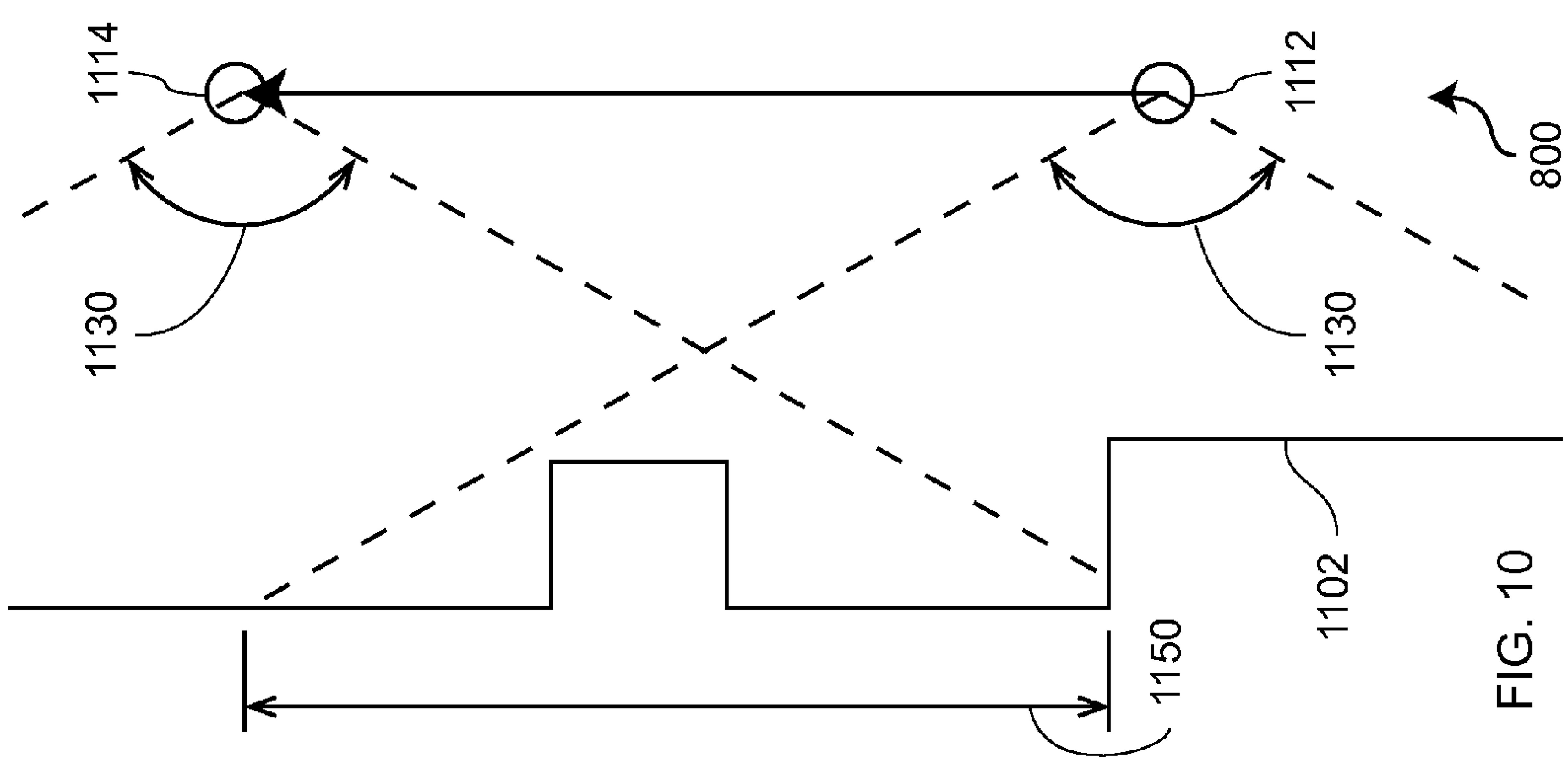
1114
1112
800
1140
1105
1104
1103
1102

FIG. 11


1114
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1130
1102
1150

FIG. 10

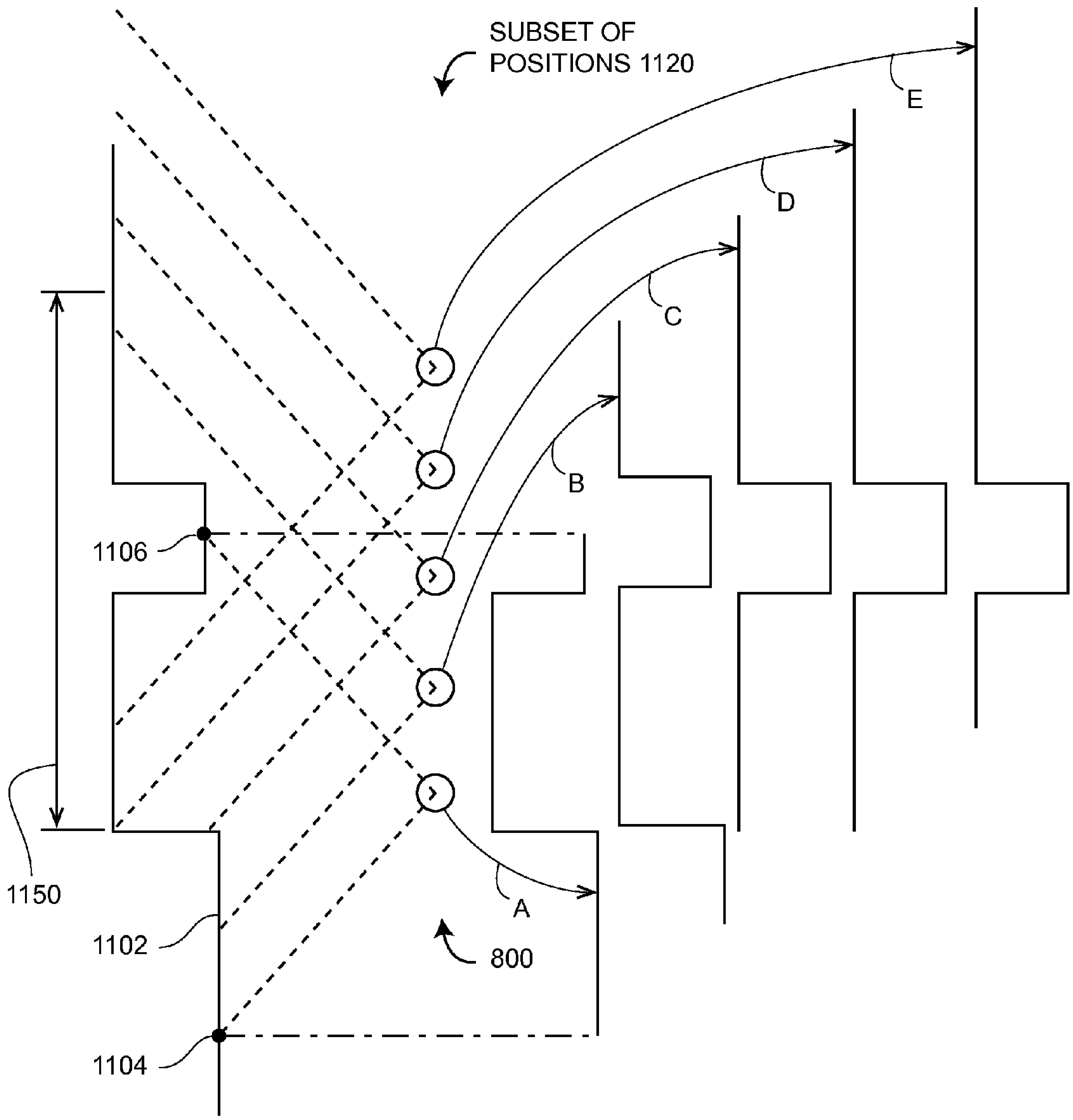

FIG. 12

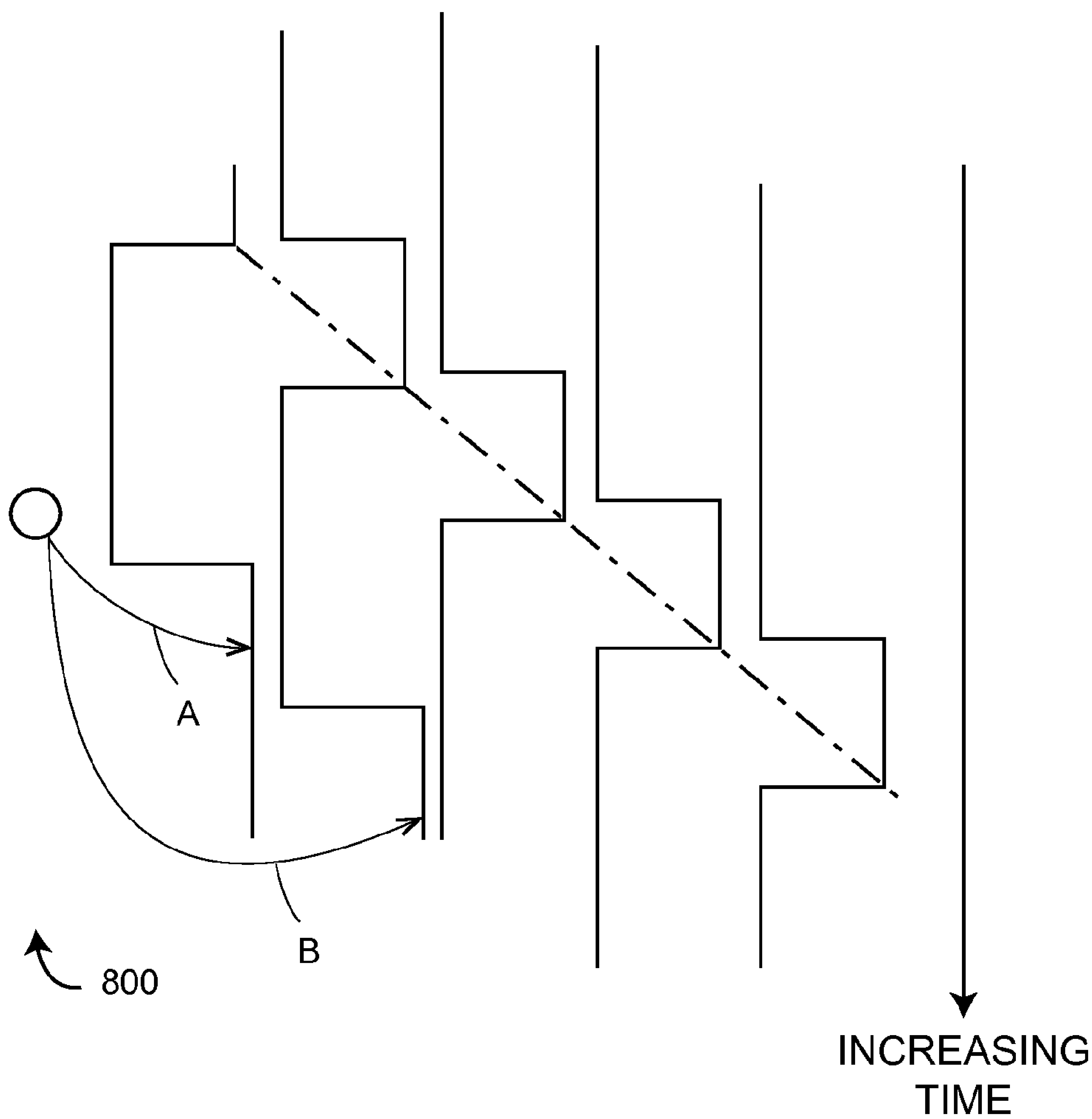

FIG. 13

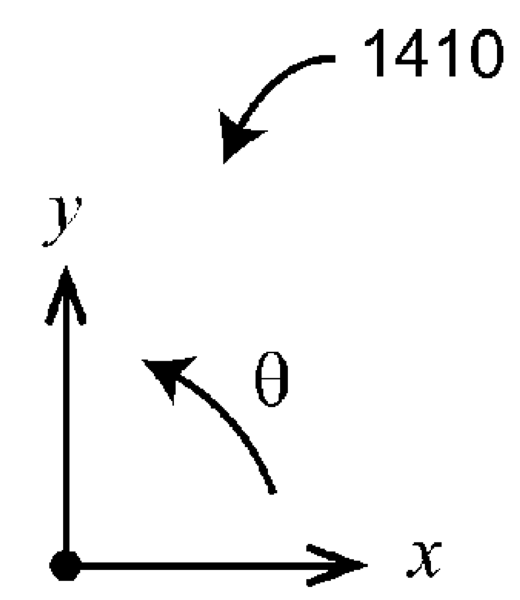

FIG. 14A

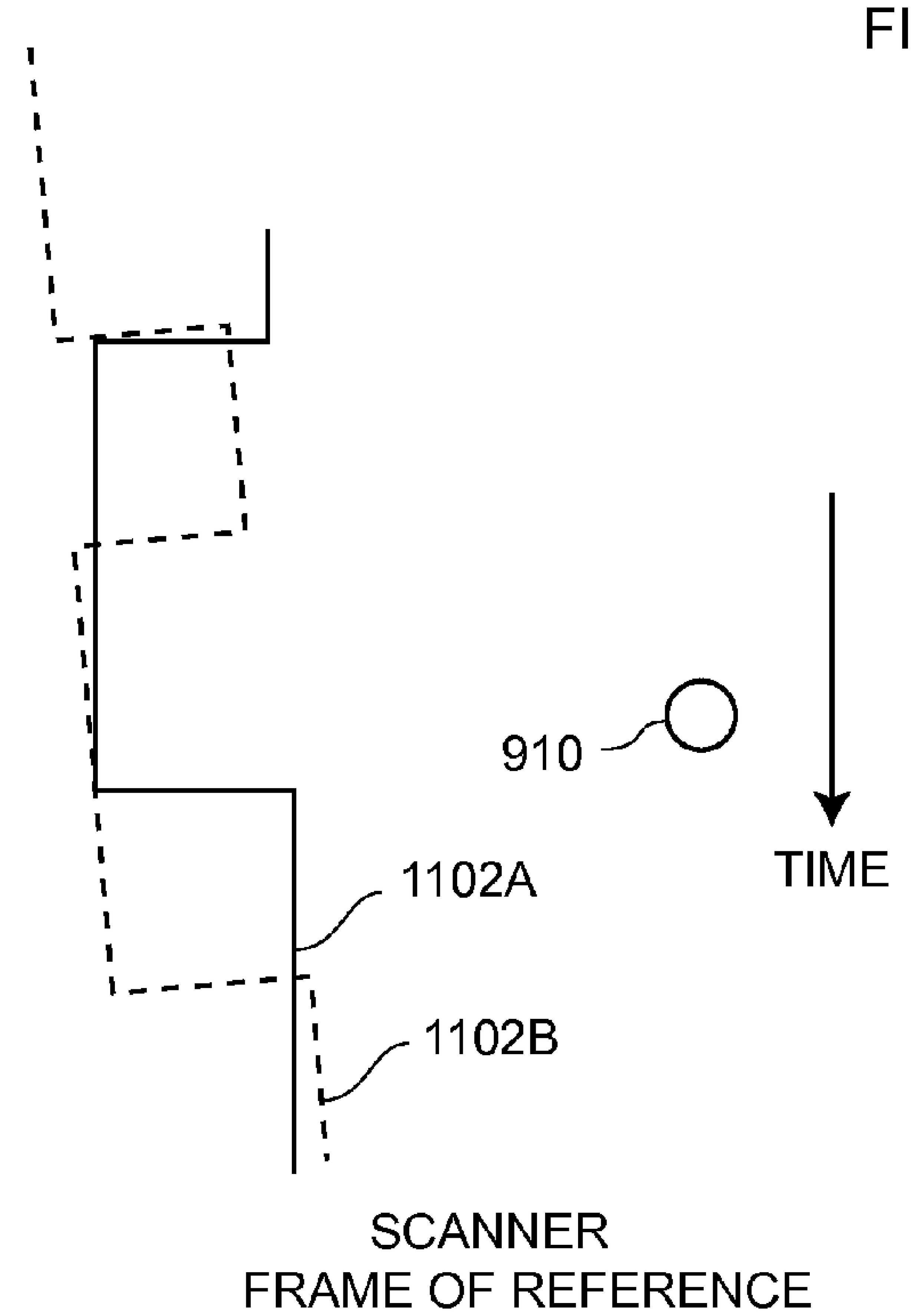

FIG. 14B

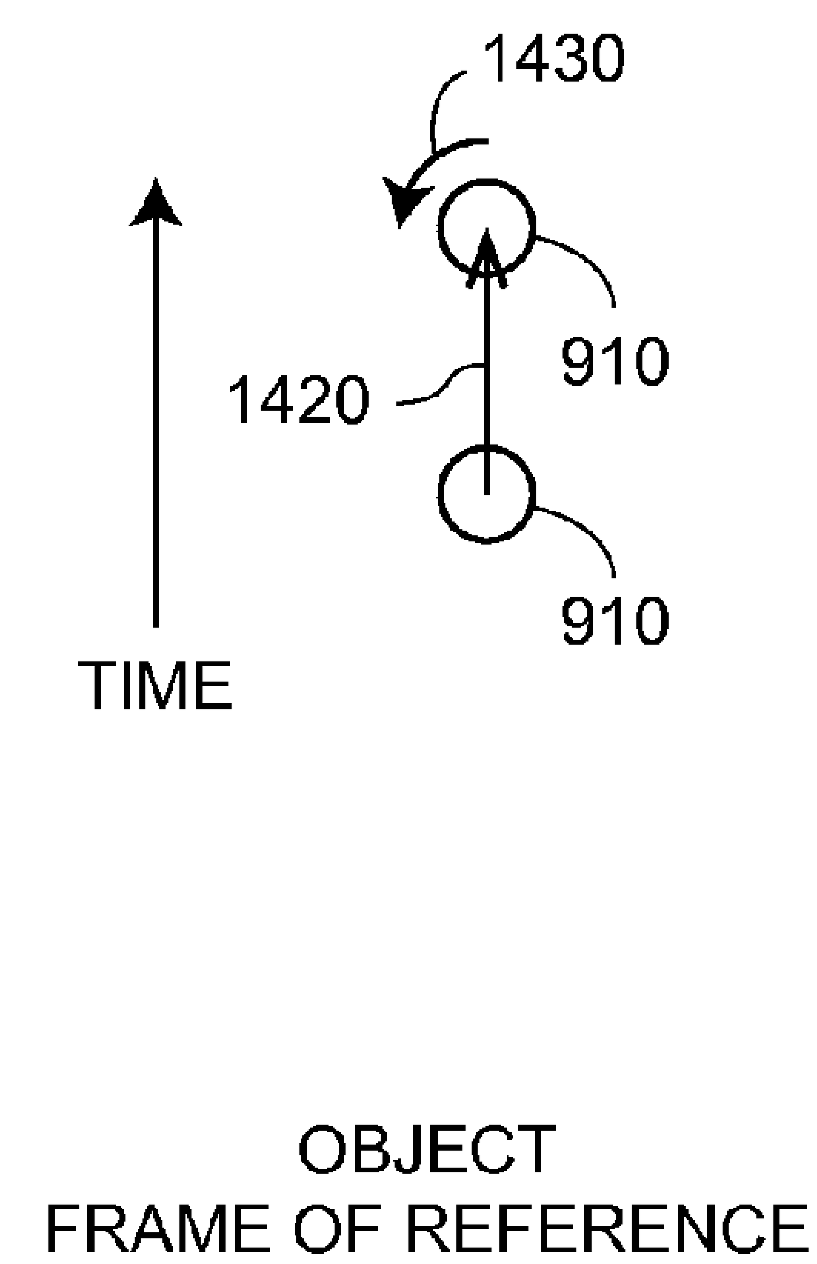

FIG. 14C

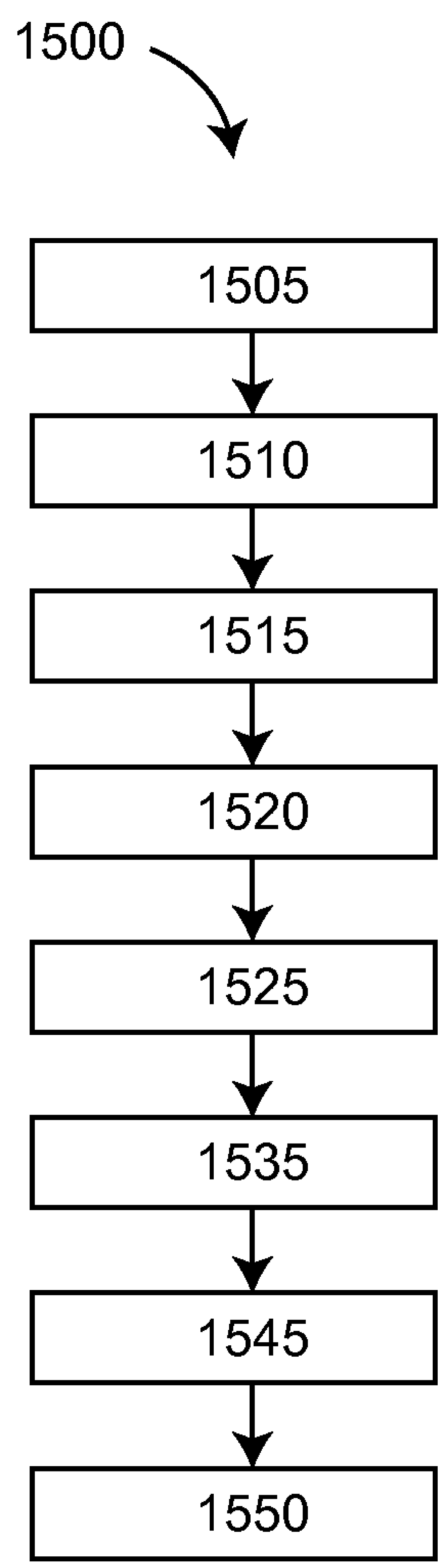

FIG. 15

USING DEPTH-CAMERA IMAGES TO SPEED REGISTRATION OF THREE-DIMENSIONAL SCANS

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application claims the benefit of International Patent Application No. PCT/IB2013/003082, filed Sep. 27, 2013, which claims the benefit of German Patent Application No. 10 2012 109 481.0, filed Oct. 5, 2012 and of U.S. Patent Application No. 61/716,845, filed Oct. 22, 2012, the contents of all of which are incorporated by reference herein.

BACKGROUND OF THE INVENTION

U.S. Pat. No. 8,705,016 ('016) describes a laser scanner which, through use of a rotatable mirror, emits a light beam into its environment to generate a three-dimensional (3D) scan. The contents of this patent are incorporated herein by reference.

The subject matter disclosed herein relates to use of a 3D laser scanner time-of-flight (TOF) coordinate measurement device. A 3D laser scanner of this type steers a beam of light to a non-cooperative target such as a diffusely scattering surface of an object. A distance meter in the device measures a distance to the object, and angular encoders measure the angles of rotation of two axles in the device. The measured distance and two angles enable a processor in the device to determine the 3D coordinates of the target.

A TOF laser scanner is a scanner in which the distance to a target point is determined based on the speed of light in air between the scanner and a target point. Laser scanners are typically used for scanning closed or open spaces such as interior areas of buildings, industrial installations and tunnels. They may be used, for example, in industrial applications and accident reconstruction applications. A laser scanner optically scans and measures objects in a volume around the scanner through the acquisition of data points representing object surfaces within the volume. Such data points are obtained by transmitting a beam of light onto the objects and collecting the reflected or scattered light to determine the distance, two-angles (i.e., an azimuth and a zenith angle), and optionally a gray-scale value. This raw scan data is collected, stored and sent to a processor or processors to generate a 3D image representing the scanned area or object.

Generating an image requires at least three values for each data point. These three values may include the distance and two angles, or may be transformed values, such as the x, y, z coordinates. In an embodiment, an image is also based on a fourth gray-scale value, which is a value related to irradiance of scattered light returning to the scanner.

Most TOF scanners direct the beam of light within the measurement volume by steering the light with a beam steering mechanism. The beam steering mechanism includes a first motor that steers the beam of light about a first axis by a first angle that is measured by a first angular encoder (or other angle transducer). The beam steering mechanism also includes a second motor that steers the beam of light about a second axis by a second angle that is measured by a second angular encoder (or other angle transducer).

Many contemporary laser scanners include a camera mounted on the laser scanner for gathering camera digital images of the environment and for presenting the camera digital images to an operator of the laser scanner. By viewing the camera images, the operator of the scanner can determine the field of view of the measured volume and adjust settings on the laser scanner to measure over a larger or smaller region of space. In addition, the camera digital images may be transmitted to a processor to add color to the scanner image. To generate a color scanner image, at least three positional coordinates (such as x, y, z) and three color values (such as red, green, blue "RGB") are collected for each data point.

A 3D image of a scene may require multiple scans from different registration positions. The overlapping scans are registered in a joint coordinate system, for example, as described in U.S. Published Patent Application No. 2012/0069352 ('352), the contents of which are incorporated herein by reference. Such registration is performed by matching targets in overlapping regions of the multiple scans. The targets may be artificial targets such as spheres or checkerboards or they may be natural features such as corners or edges of walls. Some registration procedures involve relatively time-consuming manual procedures such as identifying by a user each target and matching the targets obtained by the scanner in each of the different registration positions. Some registration procedures also require establishing an external "control network" of registration targets measured by an external device such as a total station. The registration method disclosed in '352 eliminates the need for user matching of registration targets and establishing of a control network.

However, even with the simplifications provided by the methods of '352, it is today still difficult to remove the need for a user to carry out the manual registration steps as described above. In a typical case, only 30% of 3D scans can be automatically registered to scans taken from other registration positions. Today such registration is seldom carried out at the site of the 3D measurement but instead in an office following the scanning procedure. In a typical case, a project requiring a week of scanning requires two to five days to manually register the multiple scans. This adds to the cost of the scanning project. Furthermore, the manual registration process sometimes reveals that the overlap between adjacent scans was insufficient to provide proper registration. In other cases, the manual registration process may reveal that certain sections of the scanning environment have been omitted. When such problems occur, the operator must return to the site to obtain additional scans. In some cases, it is not possible to return to a site. A building that was available for scanning at one time may be impossible to access at a later time. A forensics scene of an automobile accident or a homicide is often not available for taking of scans for more than a short time after the incident.

Accordingly, while existing 3D scanners are suitable for their intended purposes, what is needed is a 3D scanner having certain features of embodiments of the present invention.

BRIEF DESCRIPTION OF THE INVENTION

According to one aspect of the invention, a three-dimensional (3D) measuring device is provided including: a processor system including at least one of a 3D scanner controller, an external computer, and a cloud computer configured for remote network access; a 3D scanner having a first light source, a first beam steering unit, a first angle measuring device, a second angle measuring device, and a first light receiver, the first light source configured to emit a first beam of light, the first beam steering unit configured to steer the first beam of light to a first direction onto a first object point, the first direction determined by a first angle of rotation about a first axis and a second angle of rotation about a second axis, the first angle measuring device configured to measure the first angle of rotation and the second angle measuring device configured to measure the second angle of rotation, the first light receiver configured to receive first reflected light, the first reflected light being a portion of the first beam of light reflected by the first object point, the first light receiver configured to produce a first electrical signal in response to the first reflected light, the first light receiver configured to cooperate with the processor system to determine a first distance to the first object point based at least in part on the first electrical signal, the 3D scanner configured to cooperate with the processor system to determine 3D coordinates of the first object point based at least in part on the first distance, the first angle of rotation and the second angle of rotation; a moveable platform configured to carry the 3D scanner; a depth camera configured to move in conjunction with the 3D scanner; wherein the processor system is responsive to executable instructions which when executed by the processor system is operable to: cause the 3D scanner, while fixedly located at a first registration position, to cooperate with the processor system to determine 3D coordinates of a first collection of points on an object surface; cause the 3D measuring device, while moving from the first registration position to a second registration position, to cooperate with the processor system to obtain a plurality of depth-camera image sets, each of the plurality of depth-camera image sets being a set of 3D coordinates of points on the object surface, each of the plurality of depth-camera image sets being collected by the 3D measuring device at a different position relative to the first registration position; determine a first translation value corresponding to a first translation direction, a second translation value corresponding to a second translation direction, and a first rotation value corresponding to a first orientational axis, wherein the first translation value, the second translation value, and the first rotation value are determined based at least in part on a fitting of the plurality of depth-camera image sets according to a first mathematical criterion; cause the 3D scanner, while fixedly located at the second registration position, to cooperate with the processor system to determine 3D coordinates of a second collection of points on the object surface; identify a correspondence among registration targets present in both the first collection of points and the second collection of points, the correspondence based at least in part on the first translation value, the second translation value, and the first rotation value; and determine 3D coordinates of a registered 3D collection of points based at least in part on a second mathematical criterion, the determined correspondence among the registration targets, the 3D coordinates of the first collection of points, and the 3D coordinates of the second collection of points.

In a further aspect of the invention, a method for measuring and registering three-dimensional (3D) coordinates is provided including: providing a 3D measuring device that includes a processor system, a 3D scanner, a depth camera, and a moveable platform, the processor system having at least one of a 3D scanner controller, an external computer, and a cloud computer configured for remote network access, the 3D scanner having a first light source, a first beam steering unit, a first angle measuring device, a second angle measuring device, and a first light receiver, the first light source configured to emit a first beam of light, the first beam steering unit configured to steer the first beam of light to a first direction onto a first object point, the first direction determined by a first angle of rotation about a first axis and a second angle of rotation about a second axis, the first angle measuring device configured to measure the first angle of rotation and the second angle measuring device configured to measure the second angle of rotation, the first light receiver configured to receive first reflected light, the first reflected light being a portion of the first beam of light reflected by the first object point, the first light receiver configured to produce a first electrical signal in response to the first reflected light, the first light receiver configured to cooperate with the processor system to determine a first distance to the first object point based at least in part on the first electrical signal, the 3D scanner configured to cooperate with the processor system to determine 3D coordinates of the first object point based at least in part on the first distance, the first angle of rotation and the second angle of rotation, a depth camera configured to move in conjunction with the 3D scanner; the moveable platform configured to carry the 3D scanner and the depth camera; determining with the processor system, in cooperation with the 3D scanner, 3D coordinates of a first collection of points on an object surface while the 3D scanner is fixedly located at a first registration position; obtaining by the 3D measuring device in cooperation with the processor system a plurality of depth-camera image sets, each of the plurality of depth-camera image sets being collected as the 3D measuring device moves from the first registration position to a second registration position, each of the plurality of depth-camera image sets being collected by the 3D measuring device at a different position relative to the first registration position; determining by the processor system a first translation value corresponding to a first translation direction, a second translation value corresponding to a second translation direction, and a first rotation value corresponding to a first orientational axis, wherein the first translation value, the second translation value, and the first rotation value are determined based at least in part on a fitting of the plurality of depth-camera image sets according to a first mathematical criterion; determining with the processor system, in cooperation with the 3D scanner, 3D coordinates of a second collection of points on the object surface while the 3D scanner is fixedly located at the second registration position; identifying by the processor system a correspondence among registration targets present in both the first collection of points and the second collection of points, the correspondence based at least in part on the first translation value, the second translation value, and the first rotation value; determining 3D coordinates of a registered 3D collection of points based at least in part on a second mathematical criterion, the correspondence among registration targets, the 3D coordinates of the first collection of points, and the 3D coordinates of the second collection of points; and storing the 3D coordinates of the registered 3D collection of points.

These and other advantages and features will become more apparent from the following description taken in conjunction with the drawings.

BRIEF DESCRIPTION OF THE DRAWING

The subject matter, which is regarded as the invention, is particularly pointed out and distinctly claimed in the claims at the conclusion of the specification. The foregoing and other features, and advantages of the invention are apparent from the following detailed description taken in conjunction with the accompanying drawings in which:

FIG. **1** is a perspective view of a laser scanner in accordance with an embodiment of the invention;

FIG. **2** is a side view of the laser scanner illustrating a method of measurement according to an embodiment;

FIG. 3 is a schematic illustration of the optical, mechanical, and electrical components of the laser scanner according to an embodiment;

FIG. 4 depicts a planar view of a 3D scanned image according to an embodiment;

FIG. 5 depicts an embodiment of a panoramic view of a 3D scanned image generated by mapping a planar view onto a sphere according to an embodiment;

FIGS. 6A, 6B and 6C depict embodiments of a 3D view of a 3D scanned image according to an embodiment;

FIG. 7 depicts an embodiment of a 3D view made up of an image of the object of FIG. 6B but viewed from a different perspective and shown only partially, according to an embodiment;

FIG. 8A is a perspective view of a 3D measuring device according to an embodiment;

FIG. 8B is a front view of a camera used to collect depth-camera image data while the 3D measuring device moves along a horizontal plane according to an embodiment;

FIG. 8C is a perspective view of a 3D measuring device according to an embodiment;

FIG. 9 is a block diagram depicting a processor system according to an embodiment;

FIG. 10 is a schematic representation of a 3D scanner measuring an object from two registration positions according to an embodiment;

FIG. 11 is a schematic representation of a depth camera capturing depth-camera images at a plurality of intermediate positions as the 3D measuring device is moved along a horizontal plane, according to an embodiment;

FIG. 12 shows the depth camera capturing depth-camera images at a plurality of intermediate positions as the 3D measuring device is moved along a horizontal plane, according to an embodiment;

FIG. 13 shows the depth camera capturing depth-camera images at a plurality of intermediate positions as the 3D measuring device is moved along a horizontal plane, according to an embodiment;

FIGS. 14A, 14B and 14C illustrate a method for finding changes in the position and orientation of the 3D scanner over time according to an embodiment; and

FIG. 15 includes steps in a method for measuring and registering 3D coordinates with a 3D measuring device according to an embodiment.

The detailed description explains embodiments of the invention, together with advantages and features, by way of example with reference to the drawings.

DETAILED DESCRIPTION OF THE INVENTION

The present invention relates to a 3D measuring device having a 3D scanner and a depth camera. The depth camera may be an integral part of the 3D scanner or a separate camera unit. The 3D measuring device is used in two modes, a first mode in which the 3D scanner obtains 3D coordinates of an object surface over a 3D region of space and a second mode in which depth-camera images are obtained as the camera is moved between positions at which 3D scans are taken. The depth-camera images are used together with the 3D scan data from the 3D scanner to provide automatic registration of the 3D scans.

Referring now to FIGS. 1-3, a laser scanner 20 is shown for optically scanning and measuring the environment surrounding the laser scanner 20. The laser scanner 20 has a measuring head 22 and a base 24. The measuring head 22 is mounted on the base 24 such that the laser scanner 20 may be rotated about a vertical axis 23. In one embodiment, the measuring head 22 includes a gimbal point 27 that is a center of rotation about the vertical axis 23 and a horizontal axis 25. The measuring head 22 has a rotary mirror 26, which may be rotated about the horizontal axis 25. The rotation about the vertical axis may be about the center of the base 24. The terms vertical axis and horizontal axis refer to the scanner in its normal upright position. It is possible to operate a 3D coordinate measurement device on its side or upside down, and so to avoid confusion, the terms azimuth axis and zenith axis may be substituted for the terms vertical axis and horizontal axis, respectively. The term pan axis or standing axis may also be used as an alternative to vertical axis.

The measuring head 22 is further provided with an electromagnetic radiation emitter, such as light emitter 28, for example, that emits an emitted light beam 30. In one embodiment, the emitted light beam 30 is a coherent light beam such as a laser beam. The laser beam may have a wavelength range of approximately 300 to 1600 nanometers, for example 790 nanometers, 905 nanometers, 1550 nm, or less than 400 nanometers. It should be appreciated that other electromagnetic radiation beams having greater or smaller wavelengths may also be used. The emitted light beam 30 is amplitude or intensity modulated, for example, with a sinusoidal waveform or with a rectangular waveform. The emitted light beam 30 is emitted by the light emitter 28 onto the rotary mirror 26, where it is deflected to the environment. A reflected light beam 32 is reflected from the environment by an object 34. The reflected or scattered light is intercepted by the rotary mirror 26 and directed into a light receiver 36. The directions of the emitted light beam 30 and the reflected light beam 32 result from the angular positions of the rotary mirror 26 and the measuring head 22 about the axes 25 and 23, respectively. These angular positions in turn depend on the corresponding rotary drives or motors.

Coupled to the light emitter 28 and the light receiver 36 is a controller 38. The controller 38 determines, for a multitude of measuring points X, a corresponding number of distances d between the laser scanner 20 and the points X on object 34. The distance to a particular point X is determined based at least in part on the speed of light in air through which electromagnetic radiation propagates from the device to the object point X. In one embodiment the phase shift of modulation in light emitted by the laser scanner 20 and the point X is determined and evaluated to obtain a measured distance d.

The speed of light in air depends on the properties of the air such as the air temperature, barometric pressure, relative humidity, and concentration of carbon dioxide. Such air properties influence the index of refraction n of the air. The speed of light in air is equal to the speed of light in vacuum c divided by the index of refraction. In other words, $c_{air}=c/n$. A laser scanner of the type discussed herein is based on the time-of-flight (TOF) of the light in the air (the round-trip time for the light to travel from the device to the object and back to the device). Examples of TOF scanners include scanners that measure round trip time using the time interval between emitted and returning pulses (pulsed TOF scanners), scanners that modulate light sinusoidally and measure phase shift of the returning light (phase-based scanners), as well as many other types. A method of measuring distance based on the time-of-flight of light depends on the speed of light in air and is therefore easily distinguished from methods of measuring distance based on triangulation. Triangulation-based methods involve projecting light from a light source along a particular direction and then intercepting the light on a camera pixel along a particular direction. By knowing the distance between the camera and the projector and by matching a projected angle with a received angle, the method of triangulation enables the distance to the object to be determined based on one known length and two known angles of a triangle. The method of triangulation, therefore, does not directly depend on the speed of light in air.

In one mode of operation, the scanning of the volume around the laser scanner **20** takes place by rotating the rotary mirror **26** relatively quickly about axis **25** while rotating the measuring head **22** relatively slowly about axis **23**, thereby moving the assembly in a spiral pattern. In an exemplary embodiment, the rotary mirror rotates at a maximum speed of 5820 revolutions per minute. For such a scan, the gimbal point **27** defines the origin of the local stationary reference system. The base **24** rests in this local stationary reference system.

In addition to measuring a distance d from the gimbal point **27** to an object point X, the scanner **20** may also collect gray-scale information related to the received optical power (equivalent to the term “brightness.”) The gray-scale value may be determined at least in part, for example, by integration of the bandpass-filtered and amplified signal in the light receiver **36** over a measuring period attributed to the object point X.

The measuring head **22** may include a display device **40** integrated into the laser scanner **20**. The display device **40** may include a graphical touch screen **41**, as shown in FIG. **1**, which allows the operator to set the parameters or initiate the operation of the laser scanner **20**. For example, the screen **41** may have a user interface that allows the operator to provide measurement instructions to the device, and the screen may also display measurement results.

The laser scanner **20** includes a carrying structure **42** that provides a frame for the measuring head **22** and a platform for attaching the components of the laser scanner **20**. In one embodiment, the carrying structure **42** is made from a metal such as aluminum. The carrying structure **42** includes a traverse member **44** having a pair of walls **46**, **48** on opposing ends. The walls **46**, **48** are parallel to each other and extend in a direction opposite the base **24**. Shells **50**, **52** are coupled to the walls **46**, **48** and cover the components of the laser scanner **20**. In the exemplary embodiment, the shells **50**, **52** are made from a plastic material, such as polycarbonate or polyethylene for example. The shells **50**, **52** cooperate with the walls **46**, **48** to form a housing for the laser scanner **20**.

On an end of the shells **50**, **52** opposite the walls **46**, **48** a pair of yokes **54**, **56** are arranged to partially cover the respective shells **50**, **52**. In the exemplary embodiment, the yokes **54**, **56** are made from a suitably durable material, such as aluminum for example, that assists in protecting the shells **50**, **52** during transport and operation. The yokes **54**, **56** each includes a first arm portion **58** that is coupled, such as with a fastener for example, to the traverse **44** adjacent the base **24**. The arm portion **58** for each yoke **54**, **56** extends from the traverse **44** obliquely to an outer corner of the respective shell **50**, **54**. From the outer corner of the shell, the yokes **54**, **56** extend along the side edge of the shell to an opposite outer corner of the shell. Each yoke **54**, **56** further includes a second arm portion that extends obliquely to the walls **46**, **48**. It should be appreciated that the yokes **54**, **56** may be coupled to the traverse **42**, the walls **46**, **48** and the shells **50**, **54** at multiple locations.

The pair of yokes **54**, **56** cooperate to circumscribe a convex space within which the two shells **50**, **52** are arranged. In the exemplary embodiment, the yokes **54**, **56** cooperate to cover all of the outer edges of the shells **50**, **54**, while the top and bottom arm portions project over at least a portion of the top and bottom edges of the shells **50**, **52**. This provides advantages in protecting the shells **50**, **52** and the measuring head **22** from damage during transportation and operation. In other embodiments, the yokes **54**, **56** may include additional features, such as handles to facilitate the carrying of the laser scanner **20** or attachment points for accessories for example.

On top of the traverse **44**, a prism **60** is provided. The prism extends parallel to the walls **46**, **48**. In the exemplary embodiment, the prism **60** is integrally formed as part of the carrying structure **42**. In other embodiments, the prism **60** is a separate component that is coupled to the traverse **44**. When the mirror **26** rotates, during each rotation the mirror **26** directs the emitted light beam **30** onto the traverse **44** and the prism **60**. Due to non-linearities in the electronic components, for example in the light receiver **36**, the measured distances d may depend on signal strength, which may be measured in optical power entering the scanner or optical power entering optical detectors within the light receiver **36**, for example. In an embodiment, a distance correction is stored in the scanner as a function (possibly a nonlinear function) of distance to a measured point and optical power (generally unscaled quantity of light power sometimes referred to as “brightness”) returned from the measured point and sent to an optical detector in the light receiver **36**. Since the prism **60** is at a known distance from the gimbal point **27**, the measured optical power level of light reflected by the prism **60** may be used to correct distance measurements for other measured points, thereby allowing for compensation to correct for the effects of environmental variables such as temperature. In the exemplary embodiment, the resulting correction of distance is performed by the controller **38**.

In an embodiment, the base **24** is coupled to a swivel assembly (not shown) such as that described in commonly owned U.S. Pat. No. 8,705,012 (’012), which is incorporated by reference herein. The swivel assembly is housed within the carrying structure **42** and includes a motor that is configured to rotate the measuring head **22** about the axis **23**.

An auxiliary image acquisition device **66** may be a device that captures and measures a parameter associated with the scanned volume or the scanned object and provides a signal representing the measured quantities over an image acquisition area. The auxiliary image acquisition device **66** may be, but is not limited to, a pyrometer, a thermal imager, an ionizing radiation detector, or a millimeter-wave detector. In an embodiment, the auxiliary image acquisition device **66** is a color camera.

In an embodiment, a central color camera (first image acquisition device) **112** is located internally to the scanner and may have the same optical axis as the 3D scanner device. In this embodiment, the first image acquisition device **112** is integrated into the measuring head **22** and arranged to acquire images along the same optical pathway as emitted light beam **30** and reflected light beam **32**. In this embodiment, the light from the light emitter **28** reflects off a fixed mirror **116** and travels to dichroic beam-splitter **118** that reflects the light **117** from the light emitter **28** onto the rotary mirror **26**. The dichroic beam-splitter **118** allows light to pass through at wavelengths different than the wavelength of light **117**. For example, the light emitter **28** may be a near infrared laser light (for example, light at wavelengths of 780 nm or 1150 nm), with the dichroic beam-splitter **118** configured to reflect the infrared laser light while allowing visible light (e.g., wavelengths of 400 to 700 nm) to transmit through. In other embodiments, the determination of whether the light passes through the beam-splitter **118** or is reflected depends on the polarization of the light. The digital camera **112** obtains 2D images of the scanned area to capture color data to add to the scanned image. In the case of a built-in color camera having an optical axis coincident with that of the 3D scanning device, the direction of the camera view may be easily obtained by simply adjusting the steering mechanisms of the scanner—for example, by adjusting the azimuth angle about the axis **23** and by steering the mirror **26** about the axis **25**.

FIG. **4** depicts an example of a planar view of a 3D scanned image **400**. The planar view depicted in FIG. **4** maps an image based on direct mapping of data collected by the scanner. The scanner collects data in a spherical pattern but with data points collected near the poles more tightly compressed than those collected nearer the horizon. In other words, each point collected near a pole represents a smaller solid angle than does each point collected nearer the horizon. Since data from the scanner may be directly represented in rows and column, data in a planar image is conveniently presented in a rectilinear format, as shown in FIG. **4**. With planar mapping described above, straight lines appear to be curved, as for example the straight fence railings **420** that appear curved in the planar view of the 3D image. The planar view may be a 3D unprocessed scanned image displaying just the gray-scale values received from the distance sensor arranged in columns and rows as they were recorded. In addition, the 3D unprocessed scanned image of the planar view may be in full resolution or reduced resolution depending on system characteristics (e.g., display device, storage, processor). The planar view may be a 3D processed scanned image that depicts either gray-scale values (resulting from the light irradiance measured by the distance sensor for each pixel) or color values (resulting from camera images which have been mapped onto the scan). Although the planar view extracted from the 3D scanner is ordinarily a gray-scale or color image, FIG. **4** is shown as a line drawing for clarity in document reproduction. The user interface associated with the display unit, which may be integral to the laser scanner, may provide a point selection mechanism, which in FIG. **4** is the cursor **410**. The point selection mechanism may be used to reveal dimensional information about the volume of space being measured by the laser scanner. In FIG. **4**, the row and column at the location of the cursor are indicated on the display at **430**. The two measured angles and one measured distance (the 3D coordinates in a spherical coordinate system) at the cursor location are indicated on the display at **440**. Cartesian XYZ coordinate representations of the cursor location are indicated on the display at **450**.

FIG. **5** depicts an example of a panoramic view of a 3D scanned image **600** generated by mapping a planar view onto a sphere, or in some cases a cylinder. A panoramic view can be a 3D processed scanned image (such as that shown in FIG. **5**) in which 3D information (e.g., 3D coordinates) is available. The panoramic view may be in full resolution or reduced resolution depending on system characteristics. It should be pointed out that an image such as FIG. **5** is a 2D image that represents a 3D scene when viewed from a particular perspective. In this sense, the image of FIG. **5** is much like an image that might be captured by a 2D camera or a human eye. Although the panoramic view extracted from the 3D scanner is ordinarily a gray-scale or color image, FIG. **5** is shown as a line drawing for clarity in document reproduction.

The term panoramic view refers to a display in which angular movement is generally possible about a point in space, but translational movement is not possible (for a single panoramic image). In contrast, the term 3D view as used herein refers to generally refers to a display in which provision is made (through user controls) to enable not only rotation about a fixed point but also translational movement from point to point in space.

FIGS. **6**A, **6**B and **6**C depict an example of a 3D view of a 3D scanned image. In the 3D view a user can leave the origin of the scan and see the scan points from different viewpoints and angles. The 3D view is an example of a 3D processed scanned image. The 3D view may be in full resolution or reduced resolution depending on system characteristics. In addition, the 3D view allows multiple registered scans to be displayed in one view. FIG. **6**A is a 3D view **710** over which a selection mask **730** has been placed by a user. FIG. **6**B is a 3D view **740** in which only that part of the 3D view **710** covered by the selection mask **730** has been retained. FIG. **6**C shows the same 3D measurement data as in FIG. **6**B except as rotated to obtain a different view. FIG. **7** shows a different view of FIG. **6**B, the view in this instance being obtained from a translation and rotation of the observer viewpoint, as well as a reduction in observed area. Although the 3D views extracted from the 3D scanner are ordinarily a gray-scale or color image, FIGS. **6**A-C and **7** are shown as line drawings for clarity in document reproduction.

FIGS. **8**A, **8**B, **8**C and **9** show an embodiment of a 3D measuring device **800** that includes a 3D scanner **20**, a processor system **950**, an optional moveable platform **820**, and a depth camera at locations discussed further below. The 3D measuring device **800** may be a 3D TOF scanner **20** as described in reference to FIG. **1**.

The processor system **950** includes one or more processing elements that may include a 3D scanner processor (controller) **38**, an external computer **970**, and a cloud computer **980**. The processors may be microprocessors, field programmable gate arrays (FPGAs), digital signal processors (DSPs), and generally any device capable of performing computing functions. The one or more processors have access to memory for storing information. In an embodiment illustrated in FIG. **9**, the controller **38** represents one or more processors distributed throughout the 3D scanner. Also included in the embodiment of FIG. **9** are an external computer **970** and one or more cloud computers **980** for remote computing capability. In an alternative embodiment, only one or two of the processors **38**, **970**, and **980** is provided in the processor system. Communication among the processors may be through wired links, wireless links, or a combination of wired and wireless links. In an embodiment, scan results are uploaded after each scanning session to the cloud (remote network) for storage and future use. For the case in which a depth camera **840** is attached to the moveable platform **820**, the depth-camera data may be sent to the processor system through wired or wireless communication channels.

The depth cameras may be either of two types: a central-element depth camera and a triangulation-based depth camera. A central-element depth camera uses a single integrated sensor element combined with an illumination element to determine distance ("depth") and angles from the camera to points on an object. One type of central-element depth camera uses a lens combined with a semiconductor chip to measure round-trip time of light travelling from the camera to the object and back. For example, the Microsoft Xbox One includes a Kinect depth camera that uses an infrared

(IR) light source to illuminate a 640×480 pixel photosensitive array. This depth camera is used in parallel with a 640×480 pixel RGB camera that measures red, blue, and green colors. Infrared illumination is provided in the IR illuminators adjacent to the lens and IR array. Another example of a central-element depth camera includes a lens and a PMD Technologies PhotonICs 19k-S3 3D chip used in conjunction with an IR light source. The measurement distance range of this 160×120 pixel chip is scalable based on the camera layout. Many other central-element depth cameras and associated IR sources are available today. Most central-element depth cameras include a modulated light source. The light source may use pulse modulation for direct determination of round-trip travel time. Alternatively, the light source may use continuous wave (CW) modulation with sinusoidal or rectangular waveforms to obtain round-trip travel time based on measured phase shift.

FIG. **8**A shows two possible locations for a central-element depth camera. In an embodiment, the central-element depth camera **66** is located on the 3D scanner **20**. The depth camera **66** includes an integrated light source. In an alternative embodiment, the central-element depth camera **840** is located on the optional moveable platform **820**. It may be located on a base of the platform **820** or attached to one or more tripod legs, for example. In another embodiment, a central-element depth camera takes the place of central-color camera **112**. In this case, the light source may be integrated into the central-depth camera package or placed near to it so that the illumination light passes through the dichroic beam splitter **118**. Alternatively, the beam splitter **118** may not be a dichroic beam splitter but instead transmit and reflect wavelengths used by the central-element depth camera **112**. In this case, the wavelengths used by the depth camera **112** may be sent from the launch **28**, reflected off the beam splitter **118** onto the object, and reflected back from the object onto the depth camera.

The second type of depth camera is a triangulation-based depth camera. An example of such a camera is the Kinect of the Microsoft Xbox 360, which is a different Kinect than the Kinect of the Microsoft Xbox One described herein above. An IR light source on the Kinect of the Xbox 360 projects a pattern of light onto an object, which is imaged by an IR camera that includes a photosensitive array. The Kinect determines a correspondence between the projected pattern and the image received by the photosensitive array. It uses this information in a triangulation calculation to determine the distance to object points in the measurement volume. This calculation is based partly on the baseline between the projector and the IR camera and partly on the camera pattern received and projector pattern sent out. Unlike the central-element depth camera, a triangulation camera cannot be brought arbitrarily close to the light source (pattern projector) as accuracy is reduced with decreasing baseline distance. Many types of triangulation-based depth cameras are available.

FIG. **8**C shows two possible locations for a triangulation-based depth camera. In an embodiment, the triangulation-based depth camera **66** is located on the 3D scanner **20**. The depth camera **66** includes a camera **882** and a pattern projector **884**. It may also include an optional color camera **886**. In an alternative embodiment, the triangulation-based depth camera **870** is located on the optional moveable platform **820**. The depth camera **870** includes a camera **872** and a pattern projector **874**. It may also include a color camera **876**. The triangulation-based depth camera **870** may be located on a base of the platform **820** or attached to one or more tripod legs, for example. It is not generally possible to replace the central-color camera **112** with a triangulation-based depth camera because of the need for a baseline separation between the projector and the camera.

In one mode of operation of the 3D measuring device **800**, the depth camera (**112**, **70** or **840**) captures overlapping depth-camera images as the 3D measuring device is moved between positions at which 3D scans are taken. For the case in which the depth camera is an internal camera (for example, in place of the central color camera **112**) or a camera **66** mounted on the measuring head **22**, the camera may be optionally steered about the vertical axis **23** to increase the effective FOV of the depth camera. In an embodiment, the laser power from the 3D scanner is turned off as the depth-camera images are collected. In an alternative embodiment, the laser power is left on so that the 3D scanner **20** may make 2D scans in a horizontal plane while the depth-camera images are collected. For the case in which the depth camera **840** is mounted on the moveable platform **820**, the direction at which the depth camera is pointed is unaffected by rotation of horizontal axis **25** or vertical axis **23**.

The optional position/orientation sensor **920** in the 3D scanner **20** may include inclinometers (accelerometers), gyroscopes, magnetometers, and altimeters. Usually devices that include one or more of an inclinometer and gyroscope are referred to as an inertial measurement unit (IMU). In some cases, the term IMU is used in a broader sense to include a variety of additional devices that indicate position and/or orientation—for example, magnetometers that indicate heading based on changes in magnetic field direction relative to the earth's magnetic north and altimeters that indicate altitude (height). An example of a widely used altimeter is a pressure sensor. By combining readings from a combination of position/orientation sensors with a fusion algorithm that may include a Kalman filter, relatively accurate position and orientation measurements can be obtained using relatively low-cost sensor devices.

The optional moveable platform **820** enables the 3D measuring device **20** to be moved from place to place, typically along a floor that is approximately horizontal. In an embodiment, the optional moveable platform **820** is a tripod that includes wheels **822**. In an embodiment, the wheels **822** may be locked in place using wheel brakes **824**. In another embodiment, the wheels **822** are retractable, enabling the tripod to sit stably on three feet attached to the tripod. In another embodiment, the tripod has no wheels but is simply pushed or pulled along a surface that is approximately horizontal, for example, a floor. In another embodiment, the optional moveable platform **820** is a wheeled cart that may be hand pushed/pulled or motorized.

FIG. **10** shows the 3D measuring device **800** moved to a first registration position **1112** in front of an object **1102** that is to be measured. The object **1102** might for example be a wall in a room. In an embodiment, the 3D measuring device **800** is brought to a stop and is held in place with brakes, which in an embodiment are brakes **824** on wheels **822**. The 3D scanner **20** in the 3D measuring device **800** takes a first 3D scan of the object **1102**. In an embodiment, the 3D scanner **20** may if desired obtain 3D measurements in all directions except in downward directions blocked by the structure of the 3D measuring device **800**. However, in the example of FIG. **10**, in which 3D scanner **20** measures a long, mostly flat structure **1102**, a smaller effective FOV **1130** may be selected to provide a more face-on view of features on the structure.

When the first 3D scan is completed, the processor system **950** causes the 3D measuring device **800** to change from 3D scanning mode to a depth-camera imaging mode. The depth-camera imaging data is sent from the camera (**112**, **70** or **840**) to the processor system **950** for mathematical analysis. In an embodiment, the scanner begins collecting depth-camera imaging data as the 3D scanning stops. In another embodiment, the collection of depth-camera imaging data starts when the processor system **950** receives a signal such as a signal form the position/orientation sensor **920**, a signal from a brake release sensor, or a signal sent in response to a command from an operator. The processor system **950** may cause depth-camera imaging data to be collected when the 3D measuring device **800** starts to move, or it may cause depth-camera imaging data to be continually collected, even when the 3D measuring device **800** is stationary.

In an embodiment, the depth-camera imaging data is collected as the 3D measuring device **800** is moved toward the second registration position **1114**. In an embodiment, the depth-camera imaging data is collected and processed as the 3D scanner **20** passes through a plurality of 2D measuring positions **1120**. At each measuring position **1120**, the depth camera collects depth-camera imaging data over an effective FOV **1140**. Using methods described in more detail below, the processor system **950** uses the depth-camera imaging data from a plurality of depth-camera images at positions **1120** to determine a position and orientation of the 3D scanner **20** at the second registration position **1114** relative to the first registration position **1112**, where the first registration position and the second registration position are known in a 3D coordinate system common to both. In an embodiment, the common coordinate system is represented by 2D Cartesian coordinates x, y and by an angle of rotation θ relative to the x or y axis. In an embodiment, the x and y axes lie in the horizontal x-y plane of the 3D scanner **20** and may be further based on a direction of a "front" of the 3D scanner **20**. An example of such an (x, y, θ) coordinate system is the coordinate system **1410** of FIG. **14**A.

On the object **1102**, there is a region of overlap **1150** between the first 3D scan (collected at the first registration position **1112**) and the second 3D scan (collected at the second registration position **1114**). In the overlap region **1150** there are registration targets (which may be natural features of the object **1102**) that are seen in both the first 3D scan and the second 3D scan. A problem that often occurs in practice is that, in moving the 3D scanner **20** from the first registration position **1112** to the second registration position **1114**, the processor system **950** loses track of the position and orientation of the 3D scanner **20** and hence is unable to correctly associate the registration targets in the overlap regions to enable the registration procedure to be performed reliably. By using the succession of depth-camera images, the processor system **950** is able to determine the position and orientation of the 3D scanner **20** at the second registration position **1114** relative to the first registration position **1112**. This information enables the processor system **950** to correctly match registration targets in the region of overlap **1150**, thereby enabling the registration procedure to be properly completed.

FIG. **12** shows the 3D measuring device **800** collecting depth-camera imaging data at selected positions **1120** over an effective FOV **1140**. At different positions **1120**, the depth camera captures a portion of the object **1102** marked A, B, C, D, and E. FIG. **12** shows depth camera moving in time relative to a fixed frame of reference of the object **1102**.

FIG. **13** includes the same information as FIG. **12** but shows it from the frame of reference of the 3D scanner **20** while collecting depth-camera images rather than the frame of reference of the object **1102**. This figure makes clear that in the scanner frame of reference, the position of features on the object change over time. Hence it is clear that the distance traveled by the 3D scanner **20** between registration position 1 and registration position 2 can be determined from the depth-camera imaging data sent from the camera to the processor system **950**.

FIG. **14**A shows a coordinate system that may be used in FIGS. **14**B and **14**C. In an embodiment, the 2D coordinates x and y are selected to lie on a plane parallel to the horizontal plane of movement of the moveable platform. The angle θ is selected as a rotation angle in the plane, the rotation angle relative to an axis such as x or y. FIGS. **14**B, **14**C represent a realistic case in which the 3D scanner **20** is moved not exactly on a straight line, for example, nominally parallel to the object **1102**, but also to the side. Furthermore, the 3D scanner **20** may be rotated as it is moved.

FIG. **14**B shows the movement of the object **1102** as seen from the frame of reference of the 3D scanner **20** in traveling from the first registration position to the second registration position. In the scanner frame of reference (that is, as seen from the scanner's point of view), the object **1102** is moving while the depth camera is fixed in place. In this frame of reference, the portions of the object **1102** seen by the depth camera appear to translate and rotate in time. The depth camera provides a succession of such translated and rotated depth-camera images to the processor system **950**. In the example shown in FIGS. **14**A, B, the scanner translates in the +y direction by a distance **1420** shown in FIG. **14**B and rotates by an angle **1430**, which in this example is +5 degrees. Of course, the scanner could equally well have moved in the +x or −x direction by a small amount. To determine the movement of the depth camera in the x, y, θ directions, the processor system **950** uses the data recorded in successive depth-camera images as seen in the frame of reference of the scanner **20**, as shown in FIG. **14**B.

As the 3D scanner **20** collects successive depth-camera images and performs best-fit calculations of successive depth-camera images, the processor system **950** keeps track of the translation and rotation of the 3D scanner **20**. In this way, the processor system **950** is able to accurately determine the change in the values of x, y, θ as the measuring device **800** moves from the first registration position **1112** to the second registration position **1114**.

It is important to understand that the processor system **950** determines the position and orientation of the 3D measuring device **800** based on a comparison of the succession of depth-camera images and not on fusion of the depth-camera imaging data with 3D scan data provided by the 3D scanner **20** at the first registration position **1112** or the second registration position **1114**.

Instead, the processor system **950** is configured to determine a first translation value, a second translation value, and a first rotation value that, when applied to a combination of the first depth-camera image data and second depth-camera image data, results in transformed first depth-camera data that matches transformed second depth-camera data as closely as possible according to an objective mathematical criterion. In general, the translation and rotation may be applied to the first scan data from the 3D scanner, the second scan data from the 3D scanner, or to a combination of the two. For example, a translation applied to the first scan data set is equivalent to a negative of the translation applied to the second scan data set in the sense that both actions produce the same match in the transformed data sets. An example of an "objective mathematical criterion" is that of minimizing the sum of squared residual errors for those portions of the scan data judged to overlap. Another type of objective mathematical criterion may involve a matching of multiple features identified on the object. For example, such features might be the edge transitions **1103**, **1104**, and **1105** shown in FIG. **11**B.

In an embodiment, the processor system **950** extracts a horizontal slice from the depth-camera image. The resulting 2D coordinates on the horizontal plane provides information of the sort shown in FIGS. **12-14**. As explained herein above, such information may be used to provide first and second translation values and a first rotation value to provide a good starting point for 3D registration.

For the case in which the depth camera is internal to the camera, for example, taking the place of central color camera **112**, the light from depth-camera light source is sent off the mirror **26** and the scattered light is reflected off the object onto the mirror **26** and then onto the depth camera. In an embodiment, the mirror **26** is kept fixed about the horizontal axis **25** as shown in FIG. **8**B.

In most cases, a single horizontal slice is sufficient to provide accurate first and second translation values and first rotation value. However, in the event that the scanned area is nearly featureless over the horizontal slice, other methods may be used. One method is to take multiple horizontal slices, each at a different height. A scanned region that is nearly featureless at one height may include several features at a different height.

Another mathematical method that may be used to determine the first and second translation values and the first rotation value is an enhanced version of "optical flow." The mathematical method known in the art as "optical flow" is used extract information to evaluate sequentially overlapping camera images. This method is adapted from the studies of American psychologist James Gibson in the 1940s. A tutorial on optical flow estimation as used today is given in "Mathematical Models in Computer Vision: The Handbook" by N. Paragios, Y. Chen, and O. Faugeras (editors), Chapter 15, Springer 2005, pp. 239-258, the contents of which are incorporated by reference herein. For the case considered here, in which the camera is a depth camera rather than an ordinary 2D camera, depth information is further available for application to the optical-flow algorithm to further improve determination of the first and second translation values and the first rotation value. Additional mathematical methods known in the art may also be used to extract information on movement from the sequential depth-camera images.

The mathematical criterion may involve processing of the raw camera image data provided by the camera to the processor system **950**, or it may involve a first intermediate level of processing in which features are represented as a collection of line segments using methods that are known in the art, for example, methods based on the Iterative Closest Point (ICP). Such a method based on ICP is described in Censi, A., "An ICP variant using a point-to-line metric," IEEE International Conference on Robotics and Automation (ICRA) 2008.

In an embodiment, the first translation value is dx, the second translation value is dy, and the first rotation value dθ. If first depth-camera image data has translational and rotational coordinates (in a reference coordinate system) of (x_1, y_1, θ_1), then the second depth-camera image data collected at a second location has coordinates given by $(x_2, y_2, \theta_2)=(x_1+dx, y_1+dy, \theta_1+d\theta)$. In an embodiment, the processor system **950** is further configured to determine a third translation value (for example, dz) and a second and third rotation values (for example, pitch and roll). The third translation value, second rotation value, and third rotation value may be determined based at least in part on readings from the position/orientation sensor **920**.

The 3D scanner **20** collects depth-camera image data at the first registration position **1112** and more depth-camera image data at the second registration position **1114**. In some cases, these may suffice to determine the position and orientation of the 3D measuring device at the second registration position **1114** relative to the first registration position **1112**. In other cases, the two sets of depth-camera image data are not sufficient to enable the processor system **950** to accurately determine the first translation value, the second translation value, and the first rotation value. This problem may be avoided by collecting depth-camera image data at intermediate locations **1120**. In an embodiment, the depth-camera image data is collected and processed at regular intervals, for example, once per second. In this way, features are easily identified in successive depth-camera images **1120**. If more than two depth-camera images are obtained, the processor system **950** may choose to use the information from all the successive depth-camera images in determining the translation and rotation values in moving from the first registration position **1112** to the second registration position **1114**. Alternatively, the processor may choose to use only the first and last depth-camera images in the final calculation, simply using the intermediate depth-camera images to ensure proper correspondence of matching features. In most cases, accuracy of matching is improved by incorporating information from multiple successive depth-camera images.

The 3D measuring device **800** is moved to the second registration position **1114**. In an embodiment, the 3D measuring device **800** is brought to a stop and brakes are locked to hold the 3D scanner stationary. In an alternative embodiment, the processor system **950** starts the 3D scan automatically when the moveable platform is brought to a stop, for example, by the position/orientation sensor **920** noting the lack of movement. The 3D scanner **20** in the 3D measuring device **800** takes a 3D scan of the object **1102**. This 3D scan is referred to as the second 3D scan to distinguish it from the first 3D scan taken at the first registration position.

The processor system **950** applies the already calculated first translation value, the second translation value, and the first rotation value to adjust the position and orientation of the second 3D scan relative to the first 3D scan. This adjustment, which may be considered to provide a "first alignment," brings the registration targets (which may be natural features in the overlap region **1150**) into close proximity. The processor system **950** performs a fine registration in which it makes fine adjustments to the six degrees of freedom of the second 3D scan relative to the first 3D scan. It makes the fine adjustment based on an objective mathematical criterion, which may be the same as or different than the mathematical criterion applied to the depth-camera image data. For example, the objective mathematical criterion may be that of minimizing the sum of squared residual errors for those portions of the scan data judged to overlap. Alternatively, the objective mathematical criterion may be applied to a plurality of features in the overlap region. The mathematical calculations in the registration may be applied to raw 3D scan data or to geometrical representations of the 3D scan data, for example, by a collection of line segments.

Outside the overlap region **1150**, the aligned values of the first 3D scan and the second 3D scan are combined in a registered 3D data set. Inside the overlap region, the 3D scan values included in the registered 3D data set are based on some combination of 3D scanner data from the aligned values of the first 3D scan and the second 3D scan.

FIG. **15** shows elements of a method **1500** for measuring and registering 3D coordinates.

An element **1505** includes providing a 3D measuring device that includes a processor system, a 3D scanner, a depth camera, and a moveable platform. The processor system has at least one of a 3D scanner controller, an external computer, and a cloud computer configured for remote network access. Any of these processing elements within the processor system may include a single processor or multiple distributed processing elements, the processing elements being a microprocessor, digital signal processor, FPGA, or any other type of computing device. The processing elements have access to computer memory. The 3D scanner has a first light source, a first beam steering unit, a first angle measuring device, a second angle measuring device, and a first light receiver. The first light source is configured to emit a first beam of light, which in an embodiment is a beam of laser light. The first beam steering unit is provided to steer the first beam of light to a first direction onto a first object point. The beam steering unit may be a rotating mirror such as the mirror **26** or it may be another type of beam steering mechanism. For example, the 3D scanner may contain a base onto which is placed a first structure that rotates about a vertical axis, and onto this structure may be placed a second structure that rotates about a horizontal axis. With this type of mechanical assembly, the beam of light may be emitted directly from the second structure and point in a desired direction. Many other types of beam steering mechanisms are possible. In most cases, a beam steering mechanism includes one or two motors. The first direction is determined by a first angle of rotation about a first axis and a second angle of rotation about a second axis. The first angle measuring device is configured to measure the first angle of rotation and the second angle measuring device configured to measure the second angle of rotation. The first light receiver is configured to receive first reflected light, the first reflected light being a portion of the first beam of light reflected by the first object point. The first light receiver is further configured to produce a first electrical signal in response to the first reflected light. The first light receiver is further configured to cooperate with the processor system to determine a first distance to the first object point based at least in part on the first electrical signal, and the 3D scanner is configured to cooperate with the processor system to determine 3D coordinates of the first object point based at least in part on the first distance, the first angle of rotation and the second angle of rotation. The moveable platform is configured to carry the 3D scanner. The depth camera is configured to obtain depth-camera images and to send the depth-camera image data to the processor system **950**. The depth camera may be located internal to the 3D scanner, mounted on the 3D scanner, or attached to the moveable platform.

An element **1510** includes determining with the processor system **950**, in cooperation with the 3D scanner **20**, 3D coordinates of a first collection of points on an object surface while the 3D scanner is fixedly located at a first registration position.

An element **1515** includes obtaining by the 3D measuring device in cooperation with the processor system a plurality of depth-camera image sets. Each of the plurality of depth-camera image sets is a set of 3D coordinates of points on the object surface collected as the 3D scanner moves from the first registration position to a second registration position. Each of the plurality of depth-camera image sets is collected by the depth camera at a different position relative to the first registration position.

An element **1520** includes determining by the processor system a first translation value corresponding to a first translation direction, a second translation value corresponding to a second translation direction, and a first rotation value corresponding to a first orientational axis, wherein the first translation value, the second translation value, and the first rotation value are determined based at least in part on a fitting of the plurality of depth-camera image sets according to a first mathematical criterion. In an embodiment, the first orientation axis is a vertical axis perpendicular to the planes in which the depth-camera image sets are collected.

An element **1525** includes determining with the processor system, in cooperation with the 3D scanner, 3D coordinates of a second collection of points on the object surface while the 3D scanner is fixedly located at the second registration position.

An element **1535** includes identifying by the processor system a correspondence among registration targets present in both the first collection of points and the second collection of points, the correspondence based at least in part on the first translation value, the second translation value, and the first rotation value. This is a step that aligns to a relatively high accuracy level the 3D scan data collected at the first and second registration positions.

An element **1545** includes determining 3D coordinates of a registered 3D collection of points based at least in part on a second mathematical criterion, the correspondence among registration targets, the 3D coordinates of the first collection of points, and the 3D coordinates of the second collection of points. This step performs a fine registration and merges the first and second collections of points into a single registered 3D collection of points. An element **1550** includes storing the 3D coordinates of the registered 3D collection of points.

Terms such as processor, controller, computer, DSP, FPGA are understood in this document to mean a computing device that may be located within an instrument, distributed in multiple elements throughout an instrument, or placed external to an instrument.

While the invention has been described in detail in connection with only a limited number of embodiments, it should be readily understood that the invention is not limited to such disclosed embodiments. Rather, the invention can be modified to incorporate any number of variations, alterations, substitutions or equivalent arrangements not heretofore described, but which are commensurate with the spirit and scope of the invention. Additionally, while various embodiments of the invention have been described, it is to be understood that aspects of the invention may include only some of the described embodiments. Accordingly, the invention is not to be seen as limited by the foregoing description, but is only limited by the scope of the appended claims.

What is claimed is:

1. A three-dimensional (3D) measuring device comprising:

a processor system including at least one of a 3D scanner controller, an external computer, and a cloud computer configured for remote network access;

a 3D scanner having a first light source, a first beam steering unit, a first angle measuring device, a second angle measuring device, and a first light receiver, the first light source configured to emit a first beam of light, the first beam steering unit configured to steer the first beam of light to a first direction onto a first object point, the first direction determined by a first angle of rotation about a first axis and a second angle of rotation about a second axis, the first angle measuring device configured to measure the first angle of rotation and the second angle measuring device configured to measure the second angle of rotation, the first light receiver configured to receive first reflected light, the first reflected light being a portion of the first beam of light reflected by the first object point, the first light receiver configured to produce a first electrical signal in response to the first reflected light, the first light receiver configured to cooperate with the processor system to determine a first distance to the first object point based at least in part on the first electrical signal, the 3D scanner configured to cooperate with the processor system to determine 3D coordinates of the first object point based at least in part on the first distance, the first angle of rotation and the second angle of rotation;

a moveable platform configured to carry the 3D scanner;

a depth camera configured to move in conjunction with the 3D scanner;

wherein the processor system is responsive to executable instructions which when executed by the processor system is operable to:

cause the 3D scanner, while fixedly located at a first registration position, to cooperate with the processor system to determine 3D coordinates of a first collection of points on an object surface;

cause the 3D measuring device, while moving from the first registration position to a second registration position, to cooperate with the processor system to obtain a plurality of depth-camera image sets, each of the plurality of depth-camera image sets being a set of 3D coordinates of points on the object surface, each of the plurality of depth-camera image sets being collected by the 3D measuring device at a different position relative to the first registration position;

determine a first translation value corresponding to a first translation direction, a second translation value corresponding to a second translation direction, and a first rotation value corresponding to a first orientational axis, wherein the first translation value, the second translation value, and the first rotation value are determined based at least in part on a fitting of the plurality of depth-camera image sets according to a first mathematical criterion;

cause the 3D scanner, while fixedly located at the second registration position, to cooperate with the processor system to determine 3D coordinates of a second collection of points on the object surface;

identify a correspondence among registration targets present in both the first collection of points and the second collection of points, the correspondence based at least in part on the first translation value, the second translation value, and the first rotation value; and

determine 3D coordinates of a registered 3D collection of points based at least in part on a second mathematical criterion, the determined correspondence among the registration targets, the 3D coordinates of the first collection of points, and the 3D coordinates of the second collection of points.

2. The 3D measuring device of claim **1** wherein the 3D measuring device further includes a position/orientation sensor, the position orientation sensor including at least one sensor selected from the group consisting of an inclinometer, a gyroscope, a magnetometer, and an altimeter.

3. The 3D measuring device of claim **1** wherein the moveable platform is a tripod having wheels and a brake.

4. The 3D measuring device of claim **1** wherein the first beam steering unit includes a first mirror configured to rotate about a horizontal axis and a carriage that holds the first mirror configured to rotate about a vertical axis, the rotation about the horizontal axis being driven by a first motor and the rotation about the vertical axis being driven by a second motor.

5. The 3D measuring device of claim **1** wherein the processor is further configured to respond to a stopping signal to cause the 3D scanner, while fixedly located at the second registration position, to automatically begin cooperating with the processor system to determine 3D coordinates of a second collection of points on the object surface.

6. The 3D measuring device of claim **5** wherein the stopping signal is generated in response to a signal received by the processor system from the position/orientation sensor.

7. The 3D measuring device of claim **1**, wherein the registration targets are natural features of the object surface.

8. The 3D measuring device of claim **1**, wherein the depth camera is selected from the group consisting of a depth camera internal to the 3D scanner, a depth camera mounted on the 3D scanner, and a depth camera mounted on the moveable platform.

9. A method for measuring and registering three-dimensional (3D) coordinates comprising:

providing a 3D measuring device that includes a processor system, a 3D scanner, a depth camera, and a moveable platform,

the processor system having at least one of a 3D scanner controller, an external computer, and a cloud computer configured for remote network access,

the 3D scanner having a first light source, a first beam steering unit, a first angle measuring device, a second angle measuring device, and a first light receiver, the first light source configured to emit a first beam of light, the first beam steering unit configured to steer the first beam of light to a first direction onto a first object point, the first direction determined by a first angle of rotation about a first axis and a second angle of rotation about a second axis, the first angle measuring device configured to measure the first angle of rotation and the second angle measuring device configured to measure the second angle of rotation, the first light receiver configured to receive first reflected light, the first reflected light being a portion of the first beam of light reflected by the first object point, the first light receiver configured to produce a first electrical signal in response to the first reflected light, the first light receiver configured to cooperate with the processor system to determine a first distance to the first object point based at least in part on the first electrical signal, the 3D scanner configured to cooperate with the processor system to determine 3D coordinates of the first object point based at least in part on the first distance, the first angle of rotation and the second angle of rotation,

a depth camera configured to move in conjunction with the 3D scanner;

the moveable platform configured to carry the 3D scanner and the depth camera;

determining with the processor system, in cooperation with the 3D scanner, 3D coordinates of a first collection of points on an object surface while the 3D scanner is fixedly located at a first registration position;

obtaining by the 3D measuring device in cooperation with the processor system a plurality of depth-camera image sets, each of the plurality of depth-camera image sets being collected as the 3D measuring device moves from the first registration position to a second registration position, each of the plurality of depth-camera image sets being collected by the 3D measuring device at a different position relative to the first registration position;

determining by the processor system a first translation value corresponding to a first translation direction, a second translation value corresponding to a second translation direction, and a first rotation value corresponding to a first orientational axis, wherein the first translation value, the second translation value, and the first rotation value are determined based at least in part on a fitting of the plurality of depth-camera image sets according to a first mathematical criterion;

determining with the processor system, in cooperation with the 3D scanner, 3D coordinates of a second collection of points on the object surface while the 3D scanner is fixedly located at the second registration position;

identifying by the processor system a correspondence among registration targets present in both the first collection of points and the second collection of points, the correspondence based at least in part on the first translation value, the second translation value, and the first rotation value;

determining 3D coordinates of a registered 3D collection of points based at least in part on a second mathematical criterion, the correspondence among registration targets, the 3D coordinates of the first collection of points, and the 3D coordinates of the second collection of points; and

storing the 3D coordinates of the registered 3D collection of points.

10. The method of claim **9** wherein, in the element of providing a 3D measuring device that includes a processor system, a 3D scanner, a depth camera, and a moveable platform, the 3D measuring device further includes a position/orientation sensor, the position orientation sensor including at least one sensor selected from the group consisting of an inclinometer, a gyroscope, a magnetometer, and an altimeter.

11. The method of claim **9** wherein, in the element of providing a 3D measuring device that includes a processor system, a 3D scanner, a depth camera, and a moveable platform, the moveable platform is a tripod having wheels and a brake.

12. The method of claim **9** wherein, in the element of providing a 3D measuring device that includes a processor system, a 3D scanner, a depth camera, and a moveable platform, the first beam steering unit includes a first mirror configured to rotate about a horizontal axis and a carriage that holds the first mirror, the carriage configured to rotate about a vertical axis, the rotation about the horizontal axis being driven by a first motor and the rotation about the vertical axis being driven by a second motor.

13. The method of claim **12** wherein, in the element of obtaining by the 3D measuring device in cooperation with the processor system a plurality of depth-camera image sets, the first mirror is held fixed and the second mirror is held fixed.

14. The method of claim **12** wherein, in the element of obtaining by the 3D measuring device in cooperation with the processor system a plurality of range camera image sets, the first mirror rotates about the vertical axis while the horizontal axis is held fixed.

15. The method of claim **9** wherein in the element of determining with the processor system, in cooperation with the 3D scanner, 3D coordinates of a second collection of points on the object, the processor is further configured to respond to a stopping signal to cause the 3D scanner to automatically start measurement of the second collection of points.

16. The method of claim **15** wherein in the element of determining with the processor system, in cooperation with the 3D scanner, 3D coordinates of a second collection of points on the object, the stopping signal is generated in response to a signal received by the processor system from the position/orientation sensor.

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